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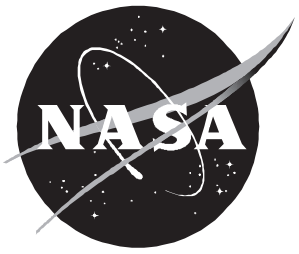

An Integrated Safety Analysis Methodology for Emerging Air Transport Technologies

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April 1998

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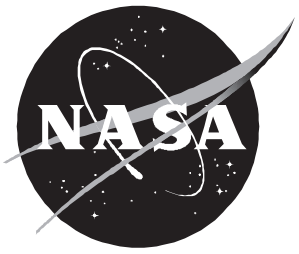

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Abstract

For NASA's air transportation research program, we demonstrate an approach to integrating reliability, performance, and operational procedure modeling into a system safety analysis. Our methodology is distinguished by its ability to merge system design/functionality information with the dynamic parameterization of a system's situation to generate accident statistics and measures of reliable system operation. In addition, this approach can be employed to perform sensitivity analyses to identify weak points in the system's operation and design.

Our approach to system safety analysis results from the *integration* of a Reliability model and an Interaction-Response model. The Interaction-Response model provides information regarding the frequency of encounters and the predicted outcome of those encounters as a function of the system's alerting system and ability to resolve encounters. The Reliability model provides, as a function of time, probabilities associated with the critical systems' availability and failure states. Scaling the conditional operational safety metrics provided by the Interaction-Response Model by the system state probabilities produced by the Reliability model creates the *system-level* safety statistics.

Products of this analysis include

- predicted incident (encounter) statistics;
- predicted accident statistics; and
- predicted false alarm statistics, as well as system availability and reliability.

As an application of this methodology, we have considered the problem of simultaneous independent approaches of two aircraft on parallel runways (independent approaches on parallel runways). An illustration of how our approach can be applied for system sensitivity analysis is also given.

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Chapter 1
Introduction and Summary

PROBLEM DEFINITION

The continuing growth of air traffic will place demands on NASA's Air Traffic Management (ATM) system that cannot be accommodated without the creation of significant delays and economic impacts. To deal with this situation, work has begun to develop new approaches to providing a safe and economical air transportation infrastructure. Many of these emerging air transport technologies will represent radically new approaches to ATM, both for ground and air operations.

The essential questions that must be answered before adopting a new approach to air transport management are as follows:

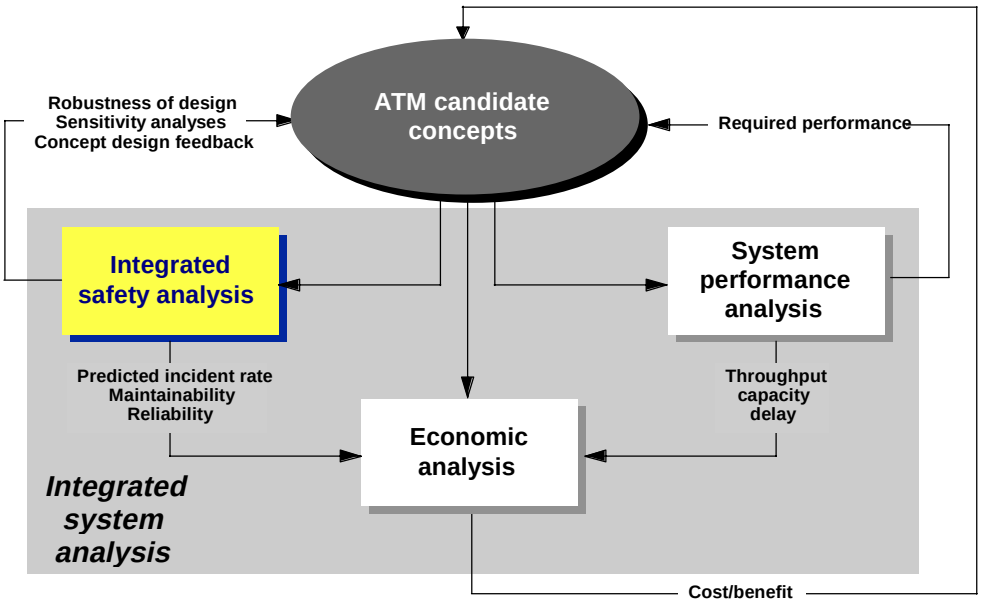
- Is the new system safe?
- What are the costs of implementing the new system?
- What are the direct economic benefits of the new system with respect to reduced delays or reduced airline costs?
- What are the indirect economic benefits of the new system with respect to deferred construction of new airports?
- What is the optimal transitioning process from the current system to the new system to ensure safety?

To answer these questions and thus select a viable ATM concept, analysis will contain

- performance models to measure delays, throughput, and aircraft density;
- safety models to measure aircraft interactions and predict accident statistics; and
- economic models to measure system costs and associated benefits.

As shown in Figure 1-1, each of these three classes of analysis models rely on the others for some of their inputs. In other words, the design, analysis, and evaluation of Air Traffic Management concepts must be treated as an interactive process in which the analyses provide crucial feedback to system developers, as well as the benefits and safety metrics required to support program advocacy.

Figure 1-1. Integrated System Analysis and Development



Thus, the primary focus in developing a methodology for integrated system analysis must be to understand and model the *interactions* among performance models, safety models, and economic models. By doing so, the methodology can be used to

- identify the drivers or weak links in the current system;
- provide guidance in selecting topics for improvement studies;
- measure net improvement in a proposed concept, distinguishing candidate concepts that represent global gains from those that solve one problem by creating another; and
- provide a foundation for cost/benefit analyses that can measure true system-wide impacts.

Products of this analysis include

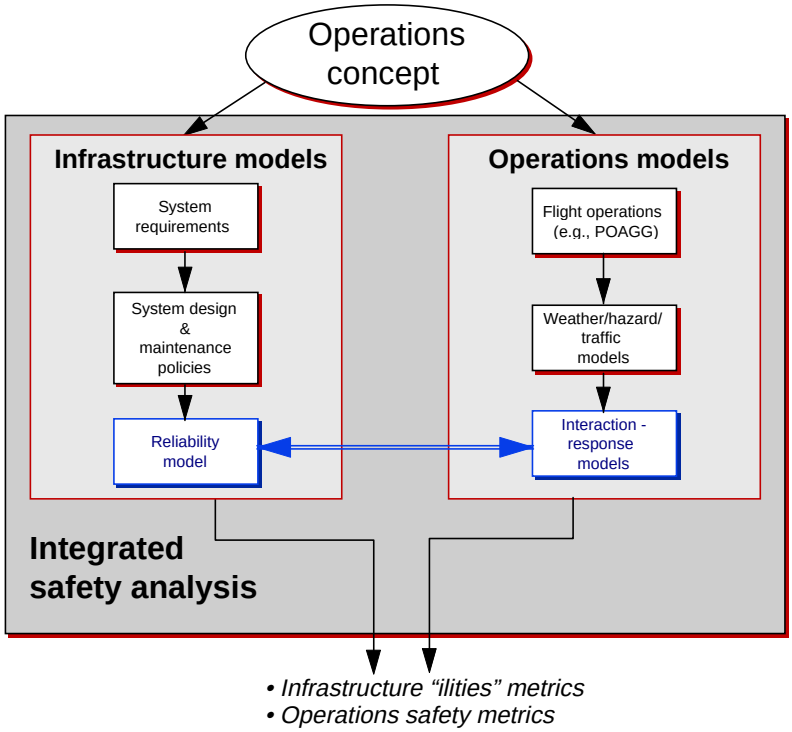
- predicted incident (encounter) statistics;
- predicted accident statistics; and
- predicted false alarm statistics, as well as system availability and reliability.

As an application of this methodology, we have considered the problem of simultaneous independent approaches of two aircraft on parallel runways (independent approaches on parallel runways [IAPR]).

INTEGRATED SYSTEM SAFETY ANALYSIS: CONCEPT, APPROACH, AND PRODUCTS

We develop and demonstrate an *integrated safety analysis methodology*, one of the key elements of an integrated system analysis capability. This methodology is distinguished by its ability to merge system design/functionality information with the dynamic parameterization of a system's situation to measure accident statistics and reliable system operation. The "system" may include both air and ground subsystems within this analysis framework. In addition, it can perform sensitivity analyses to identify weak points in the system's operation and design. This is illustrated in Figure 1-2.

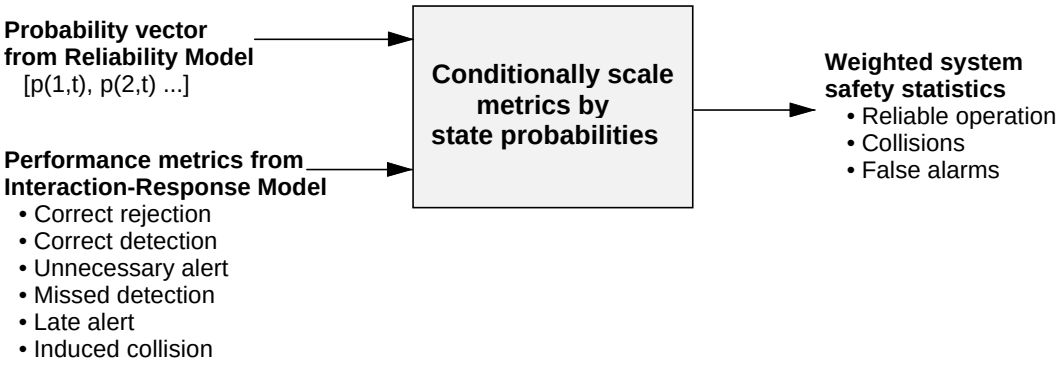
Figure 1-2. Integrated Safety and Reliability Modeling and Evaluation



On the left side of Figure 1-2 are the steps leading from requirements derived for an operational concept to the development of a Reliability Model of the system architecture, which has been proposed to meet those requirements. This represents a *traditional* reliability/safety modeling process. On the right are the models required to capture the environment in which the system is to operate, as well as the interaction of those environmental models with response models representing the execution of the rules and procedures that have been developed for the candidate concept. This represents a modeling process for the dynamic analysis of the system's situation.

Our approach to system safety analysis results from the *integration* of the Reliability Model and the Interaction-Response Model. The Interaction-Response Model provides information regarding the frequency of encounters and the predicted outcome of those encounters as a function of the system's alerting system and ability to resolve encounters. The Reliability Model provides, as a function of time, probabilities associated with the critical systems' availability and failure states. Scaling the operations safety metrics from the Interaction-Response Model by the system state probabilities from the Reliability Model creates the system-level safety statistics. This process is illustrated in Figure 1-3.

Figure 1-3. Combining Model Outputs



Products of this analysis include

- predicted accident statistics,
- predicted false alarm statistics, and
- predicted system availability and reliability.

Moreover, as the operational concept evolves, the impact of changes in system architecture, rules and procedures, and operational scenarios can be easily re-evaluated with this methodology.

Figure 1-2 makes it clear that system safety is being addressed from a variety of perspectives, each of which affects safety. These include

- system functionality, the analysis of how reliably the system components perform;
- rules and procedures, the analysis of how the system is designed to respond in both safe and unsafe situations; and
- operational scenario, the analysis of the environment in which the system is expected to operate.

Integrating models that quantify each one of these three elements creates an analysis capability that is now system-wide and responsive to ongoing changes in the definition and requirements of the operational concept.

APPLICATION TO INDEPENDENT APPROACHES ON PARALLEL RUNWAYS

As an application of this methodology, we have considered the problem of simultaneous, but independent approaches of two aircraft on parallel runways (i.e., IAPR). In visual meteorological conditions (VMC), the pilots may accept responsibility for maintaining separation between their aircraft by visual means. For approaches conducted during instrument meteorological conditions (IMC), air traffic control personnel are responsible for the separation between the aircraft. The Federal Aviation Administration (FAA) allows independent parallel approaches to be carried out in VMC with a runway separation minimum of 700 feet. In IMC, independent approaches may be conducted to runways spaced at least 4,300 feet apart. This minimum is reduced to 3,400 feet if the airport is equipped with the Precision Runway Monitor (PRM) system.

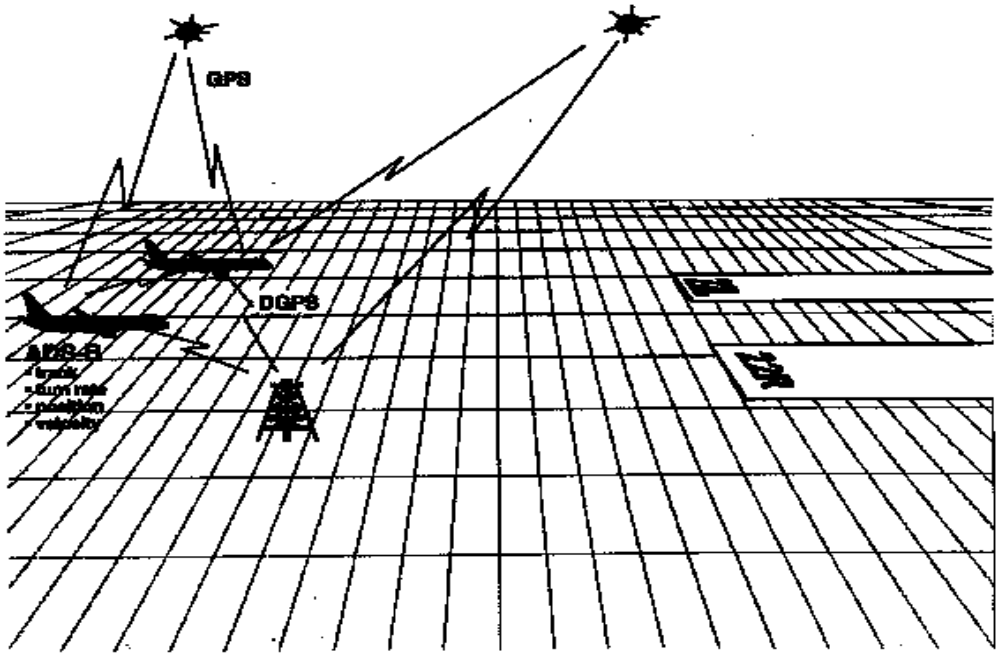
A study performed by the Boeing Commercial Airplane Group has predicted significant increases in runway capacity per hour if dependent approaches could be replaced by independent approaches. Because of capacity increases to be gained, it is desirable to reduce the minimum runway separation required for independent approaches.

A variety of projects have been undertaken within the past several years to explore alerting systems and cockpit displays for the parallel approach situation. Aircraft are more closely spaced during parallel approach than during any other phase of flight. The potential exists for an aircraft on either runway to deviate off course toward another aircraft on the parallel runway. To increase safety, an alerting system is used to warn flight crews of these blundering aircraft. The goal of the alerting system is to ensure adequate separation between aircraft while allowing parallel approaches to be carried out safely. With reference to our integrated safety model in Figure 1-2, these studies represent Interaction-Response Models.

Independent Approaches on Parallel Runways Concept and Operational Procedures

Figure 1-4 illustrates the elements of a typical IAPR concept.

Figure 1-4. Parallel Runway Concept



The IAPR system takes advantage of advances that have been made in communication, navigation, and surveillance technologies. Primary among these is GPS-based navigation and digital communications for both surveillance and pilot information exchanges (ADS-B). GPS-based navigation, with appropriate augmentation when needed, will provide much more accurate aircraft position and velocity information, reducing the need for large protective bubbles around aircraft. The accuracy and speed of the ADS-B surveillance data link system is also key to successful implementation of the IAPR concept.

The assumed operational procedure for the IAPR addressed here is as follows:

- On-board GPS system provides accurate, timely positional information of own ship.
- Position of own ship is broadcast via ADS-B.
- Positions of other ships are received and processed via ADS-B.
- Location of own ship relative to runway approach and other ships is processed and displayed on a cockpit display of traffic information (CDTI) monitor.

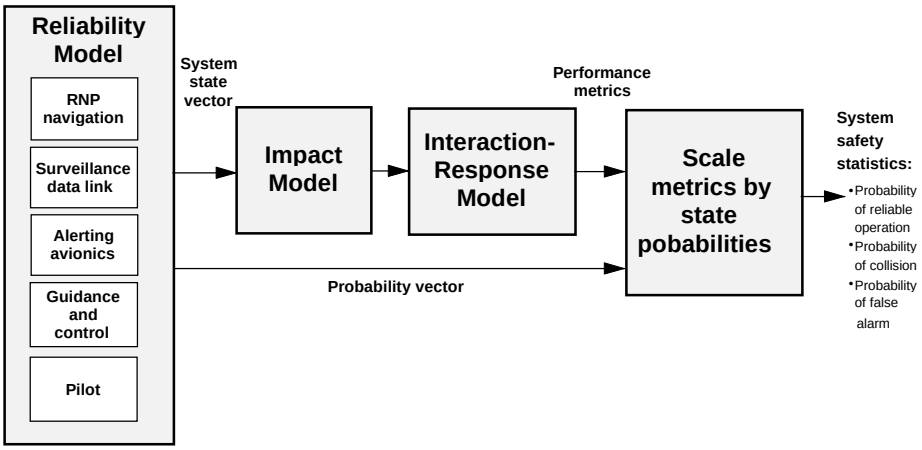
- Alerting logic sounds alert according to levels of "encounter" criteria anticipated.
- Avoidance maneuver is initiated in order to avoid "near collision" event.

Lacking any involvement of ground control, the IAPR concept just described represents a severe and possibly worst-case scenario. It is, however, more manageable from a modeling standpoint for this first application. Certainly, future work must include models for ground control interaction with aircraft.

Independent Approaches on Parallel Runways Analysis Framework Overview

Figure 1-5 illustrates the IAPR analysis framework organized with respect to four major components: system Reliability Model, Impact Model, Interaction-Response Model, and derivation of system safety statistics.

Figure 1-5. IAPR Analysis Framework



Note: RNP = required navigational performance.

Compared to Figures 1-2 and 1-3, the new feature in Figure 1-5 is the "Impact Model." The function of the Impact Model is to associate each system functional state employed in the Reliability Model with an operational capability of the aircraft and pilot. For example, a *fully operational* aircraft can execute a *normal* approach. The system functional state, *fully operational*, is associated with the flight capability, *normal approach*. Furthermore, the likelihood of the system functional state, *fully operational*, is quantified by the Reliability Model, while (conditional) safety metrics for the *normal approach* are determined from the Interaction-Response Model through a simulation process. The interaction-response simulation model includes a specific example of the alerting logic currently under investigation by NASA. The resulting system-level safety statistics are calculated by scaling the conditional safety metrics with the likelihood of the system functional state as illustrated in Figure 1-3.

An in-depth examination of each analysis component is presented in Chapter 3. The final results are summarized here in Tables 1-1 and 1-2.

Table 1-1. Combined Results at 1,700-Foot Runway Spacing

System safety statistic (t) $= \sum_{\text{Flight tracks}}$ **Pr**(simulation safety stat.| flight track) **x Pr** (flight track)(t)

Flight tracks	Conditional simulation safety statistics Rel. op.	Collisions	False alarms	Probability flight trk t = 4hrs.	t = 10 hrs
[norm_145, norm_145]	1	0	0	9.99e-1	9.98e-1
[norm_145, fake_145]	.9544	0	.0456	3.65e-6	9.1e-6
[norm_145, oadj_145]	.9125	0	.0875	3.65e-6	9.1e-6
[norm_145, sb5_145]	.996	0	.0040	1.72e-4	4.3e-4
[norm_145, sh5_145]	.9854	.0092	.0054	1.72e-4	4.3e-4
[norm_145, slo_145]	.9872	.0091	.0037	1.72e-4	4.3e-4
[norm_145, bl15_145]	.996	.0018	.0022	7.15e-6	1.8e-5
[norm_145, bl30_145]	.9872	.0037	.0091	7.15e-6	1.80e-5

System safety statistics		
Rel. op. (4)	=	0.9995
Collisions (4)	=	3.19E-6
False alarms (4)	=	2.82E-6
Rel. op. (10)	=	0.9993
Collisions (10)	=	7.97E-6
False alarms (10)	=	7.05E-6

The Reliability Model was evaluated for both 4 and 10 hours of flight prior to the aircraft beginning the runway approach. System safety statistics are computed for each time period and reflect the fact that as the time in flight increases prior to runway approach, the overall hazard increases and reliable operation decreases.

In addition to the 1,700-foot spacing, we completed a baseline evaluation at both 2,500-foot and 3,400-foot runway spacing. The three sets of safety statistics are given in Table 1-2.

Table 1-2. Safety Statistics at 1,700-Foot, 2,500-Foot, and 3,400-Foot Runway Spacings

1,700-foot spacing

System safety statistics		
Rel. op. (4)	=	0.999531
Collisions (4)	=	3.187E-6
False alarms (4)	=	2.819E-6
Rel. op. (10)	=	0.999329
Collisions (10)	=	7.968E-6
False alarms (10)	=	7.047E-6

2,500-foot spacing

System safety statistics		
Rel. op. (4)	=	0.999524
Collisions (4)	=	3.160E-6
False alarms (4)	=	1.017E-6
Rel. op. (10)	=	0.999310
Collisions (10)	=	7.901E-6
False alarms (10)	=	2.544E-6

3,400-foot spacing

System safety statistics		
Rel. op. (4)	=	0.999535
Collisions (4)	=	7.179E-7
False alarms (4)	=	1.013E-6
Rel. op. (10)	=	0.999339
Collisions (10)	=	1.796E-6
False alarms (10)	=	2.533E-6

As the runway spacing changes, only the conditional safety statistics change in response; the scaling probabilities from the Markov model remain the same. The

actual numerical values should be considered hypothetical and devised for the purposes of this example; nevertheless, the trend of the data is reasonable and what one would expect. As the time in flight increases prior to runway approach, the overall hazard increases and reliable operation decreases. As the runway spacing between aircraft increases, the probabilities of collision and false alarm decrease while reliable operation increases.

In order to demonstrate the approach, we have employed simple models. However, the approach is one wherein models can be appropriately tailored for the level of detail available or desired.

We conclude with an example of sensitivity analysis to show how this safety methodology can be used to suggest and evaluate design changes leading to improved system performance.

SENSITIVITY ANALYSIS: AN EXAMPLE

The results of the integrated safety analysis can be used to determine how sensitive the safety statistics are to features of the system architecture, rules, and operating procedures, or operational scenarios and environment. By understanding these sensitivities, design improvements can be proposed and evaluated with a cost/benefit tradeoff analysis. But the first step is to isolate the sensitivity.

Referring back to Table 1-1, *Combined Results at 1,700-Foot Runway Spacing*, observe that the slow heading change blunders of 5 and 10 degrees have the highest collision probabilities: 0.0092, and 0.0091, respectively. In addition, these tracks have the largest probabilities of occurrence with a value of 1.72E-4 at 4 hours and 4.3E-04 at 10 hours. In our example, these two tracks are associated, in part, with a degraded navigation capability such as a faulty INS subsystem.

Suppose it were possible to acquire a new, upgraded Inertial Navigation System (INS) component with a failure rate reduced from 1E-04 down to 1E-05. Replacing the “old” INS component by the new, an improved element would result in reduced probabilities of occurrence for the slow 5 and 10 degree heading blunders, namely, 5.3E-5 at 4 hours and 1.32E-4 at 10 hours.

Reevaluating the system statistics now yields improvements in collision and false alarm probabilities as shown in Table 1-3.

Table 1-3. Comparison of Results for Improved INS

Original INS	Improved INS
Collisions (4) = 3.19E-06	Collisions (4) = 1.01E-06
False alarms (4) = 2.82E-06	False alarms (4) = 1.02E-06
Collisions (10) = 7.97E-06	Collisions (10) = 2.515E-06
False alarms (10) = 7.05E-06	False alarms (10) = 2.54E-06

Note: Numbers in parentheses denote length of flight in hours.

Alternatively, a rules and procedures change could be made whereby independent parallel landings would be precluded when the aircraft is in the degraded navigation state. Costs and benefits would have to be evaluated for both the architecture option and rules/procedures option to arrive at the best course of action to improve the overall system performance and reduce the liability of accident and false alarm. In either case, the integrated safety analysis can be exercised interactively and iteratively to arrive at the best solution.

SUMMARY

We have demonstrated an approach to integrating reliability, performance, and operational procedures modeling into a system safety analysis. Our methodology is distinguished by its ability to merge system design/functionality information with the dynamic parameterization of a system's situation in order to measure accident statistics and reliable system operation. In addition, it can perform sensitivity analyses to identify weak points in the system's operation and design.

Our approach to system safety analysis results from the *integration* of the Reliability Model and the Interaction-Response Model. The Interaction-Response Model provides information regarding the frequency of encounters and the predicted outcome of those encounters as a function of the system's alerting system and ability to resolve encounters. The Reliability Model provides, as a function of time, probabilities associated with the critical systems' availability and failure states. Scaling the operations safety metrics from the Interaction-Response Model by the system state probabilities from the Reliability Model creates the system-level safety statistics. Products of this analysis include

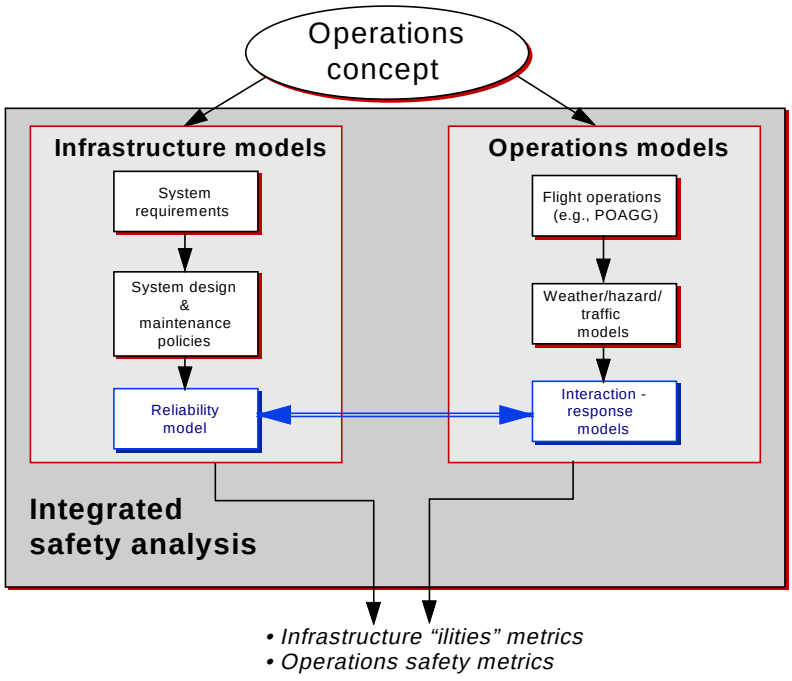
- predicted incident (encounter) statistics;
- predicted accident statistics; and
- predicted false alarm statistics, as well as system availability and reliability.

Chapter 2
Integrated Safety Analysis Overview

CONCEPT, APPROACH, AND PRODUCTS

In this report, we develop and demonstrate an integrated safety analysis methodology, one of the key elements of an integrated system analysis capability. This methodology is distinguished by its ability to merge system design/functionality information with the dynamic parameterization of a system's situation in order to measure accident statistics and reliable system operation. The "system" may include both air and ground subsystems within this analysis framework. In addition, it can perform sensitivity analyses to identify weak points in the system's operation and design. This is illustrated in Figure 2-1.

Figure 2-1. Integrated Safety and Reliability Modeling and Evaluation



On the left side of Figure 2-1 are the steps leading from requirements derived for an operational concept to the development of a reliability model of the system architecture, which has been proposed to meet those requirements. This represents a *traditional* reliability/safety modeling process. On the right are the models required to capture the environment in which the system is to operate, as well as the interaction of those environmental models with response models representing the execution of the rules/procedures that have been developed for the candidate con-

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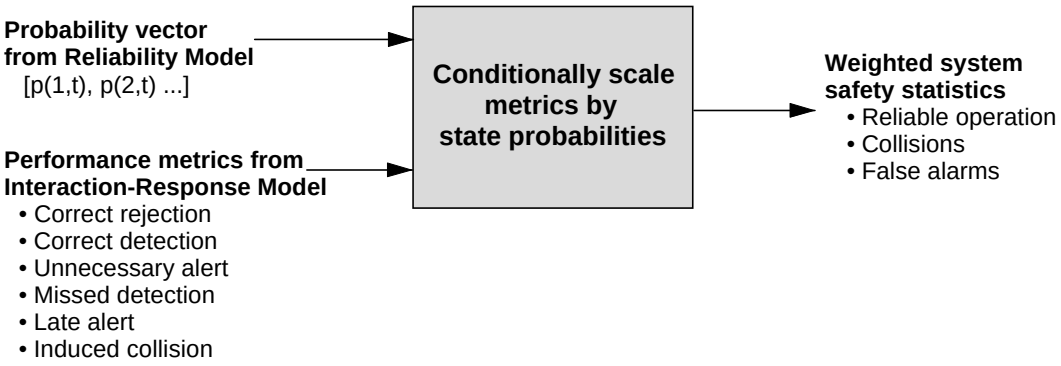
Figure 2-2. Combining Model Outputs



Products of this analysis include predicted accident statistics, predicted false alarm statistics, and predicted system availability and reliability. Moreover, as the operational concept evolves, the impact of changes in system architecture, rules and procedures, and operational scenarios can be easily accounted for with this methodology.

From Figure 2-1, it is clear that system safety is being addressed from a variety of perspectives, each of which impacts safety. These perspectives include (1) system functionality, the analysis of how reliably the system components perform; (2) rules and procedures, the analysis of how the system is designed to respond in both safe and unsafe situations; and (3) operational scenario, the analysis of the environment in which the system is expected to operate. Integrating models that quantify each one of these three elements create an analysis capability that is now system wide and responsive to ongoing changes in the definition and requirements of the operational concept.

APPLICATION TO INDEPENDENT APPROACHES ON PARALLEL RUNWAYS

As an application of this methodology, we have considered the problem of simultaneous, but independent approaches of two aircraft on parallel runways. In VMC, pilots may accept responsibility for maintaining separation between their aircraft by visual means. For approaches conducted during IMC, air traffic control personnel are responsible for the separation between the aircraft [1]. The FAA allows independent parallel approaches to be carried out in VMC with a runway separation minimum of 700 feet. In IMC, independent approaches may be conducted to runways spaced at least 4,300 feet apart. This minimum is reduced to 3,400 feet if the airport is equipped with the PRM system [2].

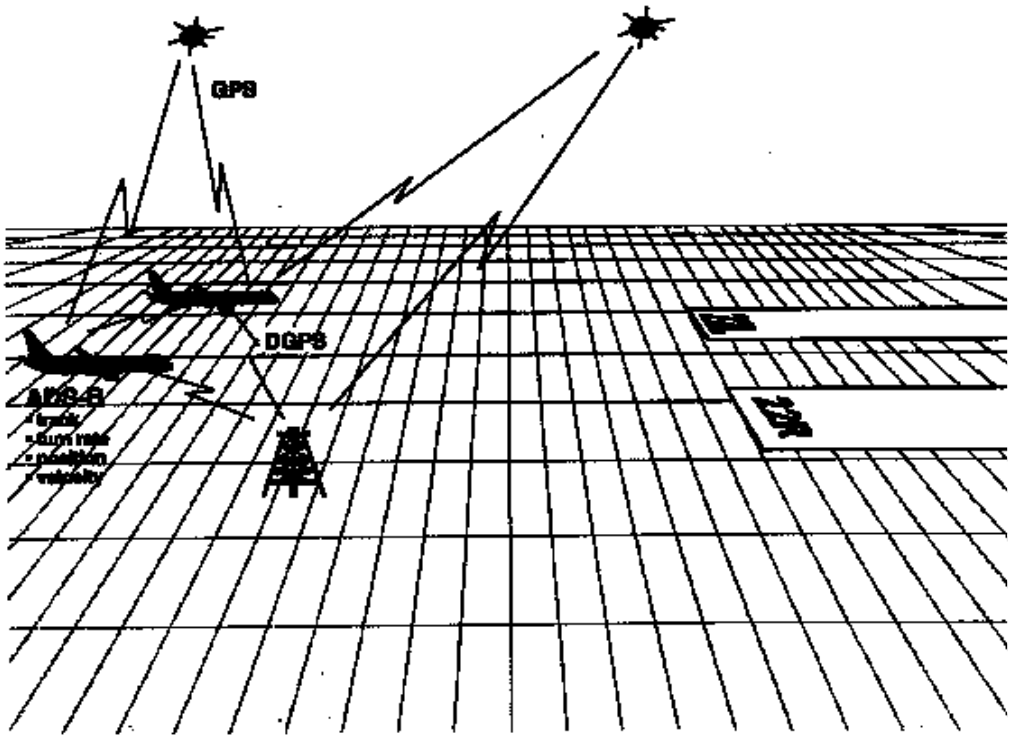
A study performed by the Boeing Commercial Airplane Group has predicted significant increases in runway capacity per hour if dependent approaches could be replaced by independent approaches [3]. Because of capacity increases to be gained, it is desirable to reduce the minimum runway separation required for independent approaches.

A variety of projects have been undertaken within the past several years to explore alerting systems and cockpit displays for the parallel approach situation [4,5,6,7,8]. Aircraft are more closely spaced during parallel approach than during any other phase of flight. The potential exists for an aircraft on either runway to deviate off course toward another aircraft on the parallel runway. To increase safety, an alerting system is used to warn flight crews of these blundering aircraft. The goal of the alerting system is to ensure adequate separation between aircraft while allowing parallel approaches to be carried out. With reference to our integrated safety model in Figure 2-1, these studies represent Interaction-Response Models.

Independent Approaches on Parallel Runways Concept and Operational Procedures

Figure 2-3 illustrates the components of a typical IAPR concept.

Figure 2-3. Parallel Runway Concepts



The IAPR system takes advantage of advances that have been made in communication, navigation, and surveillance technologies. Primary among these is GPS-based navigation and digital communications for both surveillance and pilot information exchanges (ADS-B). GPS-based navigation, with appropriate augmentation when needed, will provide much more accurate aircraft position and velocity information, reducing the need for large protective bubbles around aircraft. The accuracy and speed of the ADS-B surveillance data link system is also key to successful implementation of the IAPR concept.

The assumed operational procedure for IAPR is this:

- On-board GPS system provides accurate, timely positional information of own ship.
- Position of own ship is broadcast via ADS-B.
- Positions of other ships are received and processed via ADS-B.

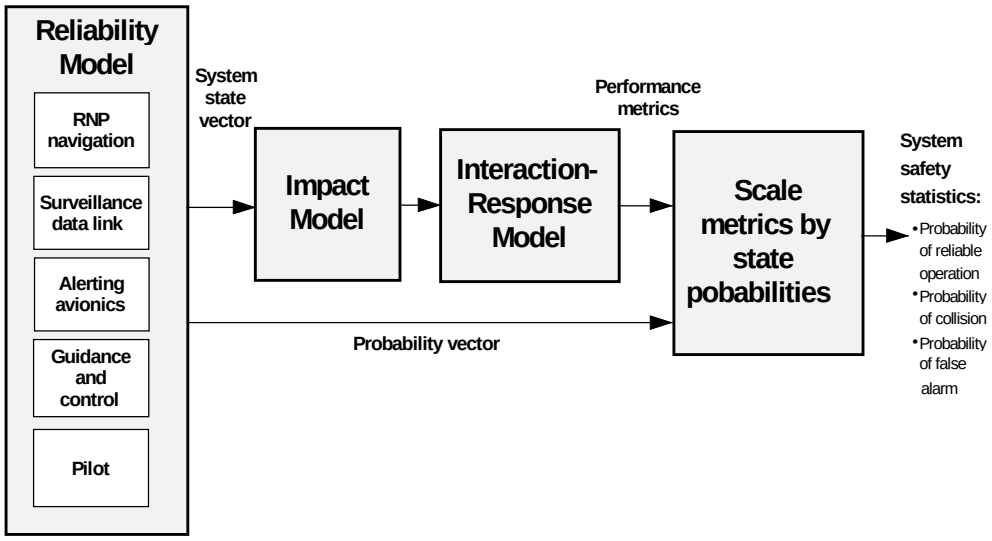
- Location of own ship relative to runway approach and other ships is processed and displayed on CDTI monitor.
- Alerting logic sounds alert according to levels of "encounter" criteria anticipated.
- Avoidance maneuver is initiated to avoid "near collision" event.

Lacking any involvement of ground control, the IAPR concept just described represents a severe and possibly "worst-case" scenario. It is, however, more manageable from a modeling standpoint for this first application. Certainly, future work must include models for ground control interaction with aircraft.

Independent Approaches and Parallel Runways Analysis Framework Overview

Figure 2-4 illustrates the IAPR analysis framework organized with respect to four major components: System Reliability Model, Impact Model, Interaction-Response Model, and Derivation of system safety statistics.

Figure 2-4. IAPR Analysis Framework



Compared with Figures 2-1 and 2-2, the new feature in Figure 2-4 is the Impact Model. The function of the Impact Model is to associate a given system functional state from the reliability model with an operational capability of the aircraft and pilot. For example, a *fully operational* aircraft can execute a *normal* approach. The system functional state, *fully operational*, is associated with the flight capability, *normal approach*. Furthermore, the likelihood of the system functional state, *fully operational*, is quantified by the Reliability Model, while (conditional) safety metrics for the *normal approach* are determined from the Interaction-Response Model through a simulation process. The resulting system-level safety

statistics are calculated by scaling the conditional safety metrics with the likelihood of the system functional state as illustrated in Figure 2-2.

An in-depth examination of each of the four analysis components is presented in Chapter 3.

Chapter 3

Independent Approaches on Parallel Runways Safety Analysis

RELIABILITY MODEL

Role of the Reliability Model

The objective of the Reliability Model is to predict the state of the aircraft capabilities at the start of and during an independent approach. In general, when an aircraft lines up for an independent approach, it will have been inflight for several hours. Assuming that the aircraft had no failures prior to takeoff, in the time from takeoff until the start of the approach, failures of components within the systems of the aircraft may have occurred that have reduced its capabilities. The reduced capabilities, possibly undetected by the pilot, can affect the performance of the aircraft during the approach and result in the aircraft drifting or blundering into the path of an aircraft approaching the adjacent runway. Alternately, the component failures during en route flight may prevent an independent approach from taking place. Procedural rules may prohibit the pilot from attempting an independent approach if there is a known loss of a specific aircraft capability or, in the worst case, failures could have caused the loss of the aircraft. The Reliability Model will calculate the probabilities of the reduced capabilities that impact the safety of the aircraft when an independent approach is attempted.

Functional Elements

The first step in developing the Reliability Model needed for the IAPR system safety model is to define the aircraft functions that directly and uniquely impact the inputs of the Interaction-Response Model. The functions, or capabilities, of the aircraft used in the IAPR system safety model are defined in Table 3-1. These functions were developed by reviewing the current status of the development of the Airborne Information for Lateral Spacing (AILS) research [6,7] and other related documentation [9,10]. However, the function definitions and the system description of the IAPR system that is presented in the next subsection are not strictly based on the AILS research. The function definitions and the system description represent the capabilities and components, respectively, that are likely to comprise an IAPR system, since a specification of an AILS system does not yet exist.

Table 3-1. IAPR System Functional Elements

Function	Definition
IAPR RNP navigation	The capability to perform conformance monitoring of an aircraft's performance and adherence to its approach path (RNP).
ADS-B/surveillance data link	The capability of an aircraft to broadcast, receive, and process ADS-B information for situational awareness, conflict avoidance, and airspace management.
Collision-alerting avionics	The capability of an aircraft to predict a probable collision with another aircraft during approach and landing and to provide timely and reliable alerts so that the pilot can avoid the collision (this includes alerting logic, processing, and display monitors).
Guidance and control	The aggregate of all other aircraft capabilities and support subsystems exclusive of the previous three functions (e.g., propulsion, flight control, and engine control).
Pilot	The capability of the pilot(s) to safely operate the aircraft.

The function definitions are limited to the capabilities of a single aircraft. The IAPR system is an aircraft-based collision-avoidance system, but there may be dependencies on systems external to the aircraft that can affect safety. The dependencies with the aircraft that may be approaching the adjacent runway will be accounted for because the same function definitions are applied to the adjacent aircraft. The dependencies on systems exclusive of the two aircraft are not included in the Reliability Model. These would include any monitoring and interaction from the ground controller or interaction with other aircraft in the airport area.

The functions defined in Table 3-1 are the capabilities of the aircraft required for an independent approach. The first three functions represent capabilities that need to be added to present commercial aircraft to support IAPR. The fourth function, guidance and control, represents all the capabilities and systems of the aircraft, exclusive of those required for the first three functions, which can affect safety of an independent approach. The fifth function isolates the capability the pilot (and crew) provides in the safe operation of the aircraft.

System Description

The system description that follows defines the reliability characteristics of the IAPR system. That is, the system description that will be presented defines the individual components that can fail, how they are interconnected, the redundancy of the components and subsystem functions, and the redundancy management logic.

To demonstrate the safety analysis methodology, a low-fidelity description of a plausible IAPR system is created. A design for the IAPR system does not exist now. So, a system is created providing the functionality expected for an IAPR system [6, 7] and includes some degree of fault tolerance. The system description constructed is complex enough to demonstrate the application of the safety analysis methodology, but simple enough so minimal resources would be needed to develop the Reliability Model. The low-fidelity model does not limit the approach.

Each system component in the system description is assigned to only one function to maintain the independence of the functions. The advantage of maintaining the independence of the functions is that it enables the probability of any system state to be computed in a simple and direct manner. For example, the probability of the system being *fully operational*, at some time *t*, is simply the product of the probabilities of each of the functions being in their fully operational states at time *t*.

Figures 3-1 through 3-4 present the block diagrams for the system description. These are discussed in the next subsections. However, to comprehend the block diagrams, several conventions need to be defined.

- Components shown with broken lines are assigned to another function. They are included in the block diagrams of some of the functions to indicate the interconnection between the components of different functions and are not considered one of the components necessary for the function.
- Duplicate blocks indicate dual-redundant components. Dual-redundant components are both on-line if functional, but only one is necessary for the function to be fully operational.
- The connections between components shown should be understood to indicate that the connected components are fully cross-strapped. For example, in Figure 3-1 the connection between the navigation processors and the navigation displays indicated by the arrow means each of the two navigation processors is connected to each of the navigation displays.

IAPR-RNP SYSTEM

Figure 3-1 presents the block diagram of the IAPR RNP system. The six components shown with solid lines provide the IAPR RNP function defined in Table 3-1. The Global Positioning System (GPS) receiver and INS provide the sensed position of the aircraft. The GPS receiver provides discrete position updates at fixed intervals in time. The INS data are integrated with the position updates from the GPS receiver to provide a more frequent position update than can be obtained with the GPS receiver alone. The data fusion and the navigation computation are done in the navigation processor. The navigation displays provide flight crews with navigation information and with alerts when navigation containment is violated.

Figure 3-1. IAPR RNP

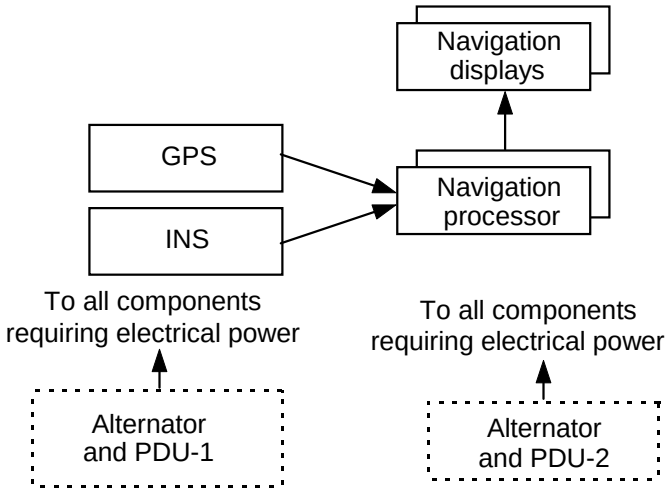


Table 3-2 presents the operational states of the IAPR RNP Navigation functions that are pertinent to the IAPR safety model. The IAPR RNP Navigation system is fully operational if both the GPS receiver and the INS 1 navigation processor and 1 navigation displays are functional. The system is degraded if either the GPS or INS has failed, the failures are detected and compensated for, and an indication has been given to the pilot by the system. The failed-safe state is the state of the system when component failures have caused the loss of the IAPR RNP navigation function and an indication is provided to the pilot to indicate this capability no longer is available. Alternately, the failed-uncovered state represents the loss of the function, but an indication is not provided to the pilot to indicate the loss of this capability.

Table 3-2. IAPR RNP Navigation Operational States

State	Definition	Impact
Fully operational	TSE (total system error) is less than containment limit and no alert of loss of RNP capability	Navigation capability available for normal approach; ideal distributions
Degraded	Loss of either GPS or INS resulting in a degraded navigation capability	Navigation capability available for normal approach; nonideal distributions
Failed safe	Alert of loss of RNP capability	No longer able to perform independent approaches; approach aborted
Failed uncovered	TSE is greater than containment limit and no alert of loss of RNP capability	Invalid self-knowledge and broadcast of navigation data

ADS-B/SURVEILLANCE DATA LINK

Figure 3-2 shows the block diagram of the ADS-B/Surveillance Data Link system. The ADS-B/Surveillance Data Link system transmits the IAPR state variable data for the aircraft (which the aircraft performing an independent approach on the adjacent runway can monitor) and receives the IAPR state variable data from the adjacent aircraft. The IAPR state variable data broadcast from the aircraft enables the Collision-Alerting Avionics of other aircraft to predict a collision. Conversely, the IAPR state variable data the aircraft receives from other aircraft enables it to predict a collision with these aircraft. The Attitude Heading Reference System (AHRS), GPS receiver, and INS provide the sensor data that make up the IAPR state variable data. However, these three sensors provide redundant information, and sufficient data are available if two of the three are functional. (Note that the GPS receiver and the INS are not included in the ADS-B/Surveillance Data Link function, having already been included in the IAPR RNP navigation function.)

Figure 3-2. ADS-B/Surveillance Data Link

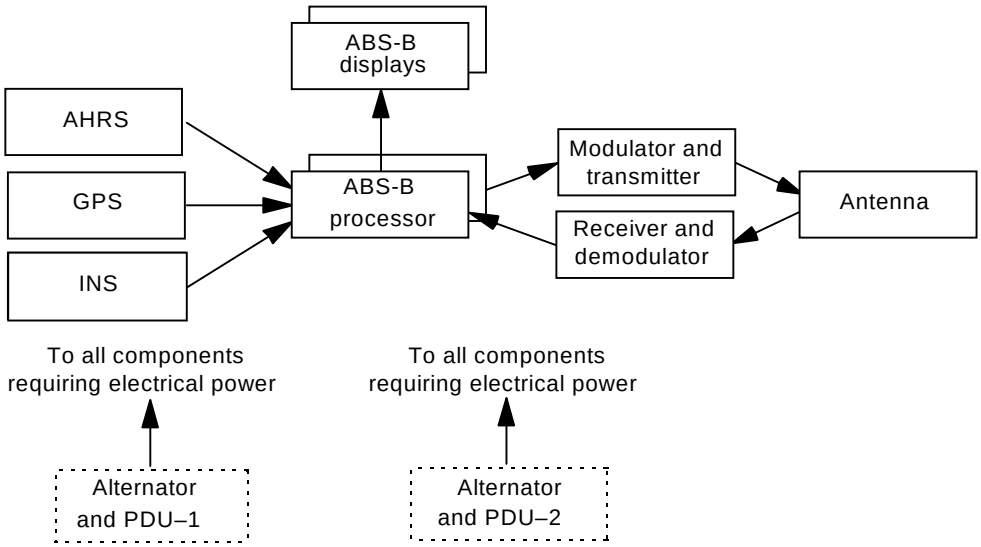


Table 3-3 presents the operational states of the ADS-B/Surveillance Data Link function. For the ADS-B/Surveillance Data Link function to be fully operational, one ABS-B processor, one ABS-B display, the modulator and transmitter, the receiver and demodulator, and the antenna must be functional. The degraded, failed-safe, and failed-uncovered states are defined in Table 3-3.

Table 3-3. ADS-B/Surveillance Data Link Operational States

State	Definition	Impact
Fully operational	Valid broadcast and reception of broadcasts from other aircraft	Transmit and receive functions are fully available
Degraded	Unable to receive broadcasts from other aircraft and may or may not receive alert of capability loss; broadcast capability functioning	Knowledge of other aircraft is invalid but approach is allowed
Failed safe	Invalid broadcast and alert of capability loss and, possibly also, loss of reception capability of broadcasts from other aircraft	No longer able to perform independent approaches; approach aborted
Failed uncovered	Invalid broadcast and no alert of capability loss	Other aircraft do not receive valid surveillance data

COLLISION-ALERTING AVIONICS

The Collision-Alerting Avionics block diagram and operational states are shown in Figure 3-3 and Table 3-4, respectively. The Collision-Alerting Avionics is fully operational if one alerting processor and one alerting displays are functional. The alerting processor receives the position of its own aircraft from the IAPR RNP navigation system and the IAPR state variable data from the aircraft approaching on the adjacent runway from the ADS-B/Surveillance Data Link system.

Figure 3-3. Collision-Alerting Avionics

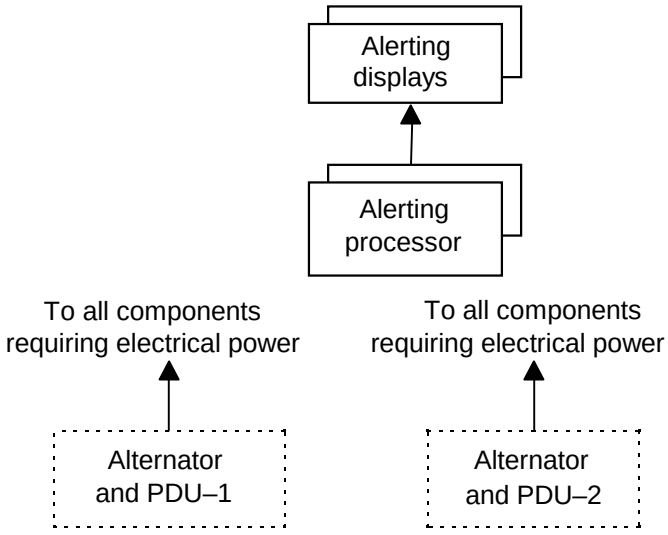


Table 3-4. Collision-Alerting Avionics Operational States

State	Definition	Impact
Fully operational	Collision-alerting capability functioning properly	Alerting capability available for normal approach
Failed safe	Collision alerting not available and alert of capability loss	No longer able to perform independent approaches; approach aborted
Failed uncovered	Collision alerting not available and no alert of capability loss	Unable to detect blunders of other aircraft but approach is not aborted

GUIDANCE AND CONTROL AND PILOT

Figure 3-4 shows the block diagram of the Guidance and Control and Pilot systems. The pilot and crew are included here as the block denoted "Pilot." The Guidance and Control system simply represents all the systems of the aircraft exclusive of the IAPR RNP navigation, ADS-B/Surveillance Data Link, and Collision-Alerting Avionics, which impact safety. The pilot provides inputs to engine and flight control to ultimately direct the thrust and flight path of the aircraft. Propulsion is provided via the engines. Engine control is provided by the engine processor using input from the pilot and engine sensors. Flight control is through the control processor, which moves the control surfaces based on inputs from the pilots and aircraft state and environment sensors. The alternator and power distribution units (PDUs) generate and distribute electrical power to all components requiring it.

Figure 3-4. Guidance and Control and Pilot Systems

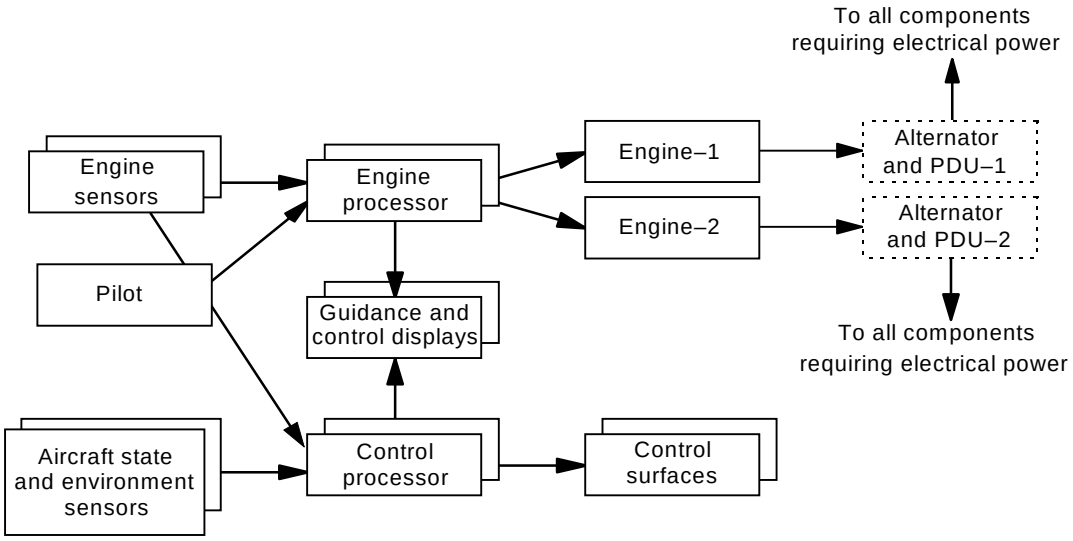


Table 3-5 presents the operational states of the guidance and control function. The guidance and control system is fully operational if one engine sensors, one aircraft state and environmental sensors, one engine processor, one control processor, one guidance and control displays, both engines, one control surfaces, and one alternator and PDU are functional. The failed-safe state would result from the covered failure of one engine. Any uncovered failures or covered failures that result in the system not satisfying the definition of fully operational would place the guidance and control function in the failed-uncovered state.

Table 3-5. Guidance and Control Operational States

State	Definition	Impact
Fully operational	All other capabilities and support subsystems operational	Capability is fully available for normal approach
Failed safe	Loss of sufficient capability and knowledge of loss	No longer able to perform independent approaches; approach aborted
Failed-uncovered	Loss of sufficient capability and no knowledge of loss or inability to control aircraft	Worst-case blunder

Table 3-6 presents the operational states of the pilot function. The pilot function is meant to capture the effect of human error in the safety of an independent approach. While an actual model of the reliability of the human in the control of the aircraft is beyond the level of work being presented here, the pilot function can still be broken down into operational states to demonstrate how the reliability of the human is integrated in the safety analysis methodology.

Table 3-6. Pilot Operational States

State	Definition	Impact
Fully operational	Pilot functioning nominally without any faults	Alerting capability available for normal approach
Recoverable fault	Pilot fault has occurred; is possible to recover from fault	No impact prior to approach; aircraft blunder after start of approach
Nonrecoverable fault	Pilot fault has occurred; is not possible to recover from fault	No impact prior to approach; aircraft blunder after start of approach

Models

A set of Markov Reliability Models are constructed from the system described in the System Description subsection. The Markov models are developed in accordance with the techniques presented in *Reliability Modeling Methodology for IAPR Safety Analysis* [11]. A separate model is constructed for each function de-

fined in Table 3-1. The input files specifying each Markov model to the Semi-Markov Unreliability Range Evaluator (SURE) Reliability Analysis Program [12] are included in Appendix A. The input files completely specify the Markov Reliability Models.

Appendix A also includes Table A-1, which provides the mapping from the numerical states of each Markov model to the operational states for each function defined in the Tables 3-2 through 3-6, respectively. Each state of each Markov model is part of one, and only one, of the operational states of one function. Note that in Table A-1, the operation state "Unknown" is added for the ADS-B/Surveillance Data Link and guidance and control functions. This state results from applying a modeling technique referred to as *Model Truncation* to reduce the number of states in these Markov models [11].

Results and Discussion

The Markov Reliability Models in the last subsection are used to calculate the probabilities of being in the operational states of each of the functions. Table 3-7 presents the baseline failure rates and coverage probabilities for each of the components identified in the system description for the IAPR system. The failure rates and coverage probabilities constitute nearly all the input parameters for the models. The only missing input parameter is recovery rate from an intermittent human failure for the pilot model. The baseline value for this rate is set at $3.6 * 10^2$ recoveries per hour.

The input parameters used are not from any specific source and are selected with the intent to highlight the fidelity of the Markov Reliability Models. Typical values of failure rates and coverage probabilities are assigned for the components that are likely to comprise the system. The failure and recovery rates for the Pilot model are not based on any empirical data.

Table 3-8 shows the calculated probabilities for the operational states of each function. The Markov models are evaluated using version 7.9.8 of the SURE Reliability Analysis Program developed by NASA Langley Research Center [12]. The Markov model state probabilities are calculated for 4 and 10 hours. These represent two time intervals from aircraft takeoff to the lineup point for an independent approach.

Note that the results in Table 3-8 are presented as bounds on the probabilities of being in the states of each function. The bounds occur from two sources. The first source, which affects all of the models, is that the SURE program calculates and outputs the bounds of the probability of being in the states of the model (numerical approximation error). The second source, which affects just the ADS-B/Surveillance Data Link and guidance and control Markov models, is the model truncation aggregation technique used to limit the size of these models. Model truncation introduces some uncertainty into the predictions [11].

Table 3-7. Baseline Failure Rates and Coverage Probabilities

Component	Failure Rate (failures/hour)	Coverage Probability
IAPR RNP Navigation		
GPS	3.0E-5	0.99
INS	1.0E-4	0.99
Navigation displays	2.0E-5	0.999, 0.99
Navigation processor	1.0E-5	0.99, 0.95
ADS-B/surveillance data link		
AHRS	1.0E-5	0.99
ADS-B displays	2.0E-5	0.999, 0.99
ADS-B processor	1.0E-5	0.99, 0.95
Modulator and transmitter	5.0E-5	0.99
Receiver and demodulator	5.0E-5	0.99
Antenna	1.0E-6	1.00
Collision-alerting logic		
Alerting displays	2.0E-5	0.999, 0.99
Alerting processor	1.0E-5	0.99, 0.95
Guidance and control		
Engine sensors	4.0E-5	0.99
Engine processor	1.0E-5	0.99
Engine	1.0E-5	0.999
Alternator and PDU	2.0E-5	0.99
Guidance and control displays	2.0E-5	0.999
State and environment sensors	4.0E-5	0.99
Control processor	1.0E-5	0.99
Control surfaces	5.0E-6	0.99
Pilot		
Intermittent human failure	1.0E-4	1.00
Permanent human failure	1.0E-6	1.00

Note: For coverage probabilities entered as two numbers, the first number is the coverage probability of first failure in redundant components, and the second number is for second failure in the redundant components.

The probabilities shown in Table 3-8 are used by the Impact Model discussed in the following section. However, there are some system probabilities produced by the Markov Reliability Models that are also of interest. Some component failures occurring before the approach lineup can preclude an independent approach. Table 3-9 presents two metrics of interest. The first is the probability that insufficient capability is available to attempt an independent approach and the approach is aborted by the pilot. This is the probability that one or more of the functions, excluding the pilot function, is in its failed-safe operational state. The second metric is the probability of a loss of the aircraft before the approach lineup. This is the probability of being in the failed-uncovered operational state of the guidance and control function.

Table 3-8. Probabilities of Operational States

Operational state	Probability of being operational state			
	At 4 hours		At 10 hours	
	Lower bound	Upper bound	Lower bound	Upper bound
IAPR RNP navigation				
Fully operational	9.9948E-1	9.9948E-1	9.9870E-1	9.9870E-1
Degraded	5.15E-4	5.15E-4	1.29E-3	1.29E-3
Failed safe	5.49E-8	5.49E-8	3.43E-7	3.43E-7
Failed uncovered	6.16E-6	6.16E-6	1.54E-5	1.54E-5
ADS-B/surveillance data link				
Fully operational	9.9959E-1	9.9960E-1	9.9899E-1	9.9899E-1
Degraded	2.00E-4	2.00E-4	5.00E-4	5.00E-4
Failed safe	2.02E-4	2.02E-4	5.05E-4	5.05E-4
Failed uncovered	2.96E-6	2.96E-6	7.40E-6	7.41E-6
Collision-alerting logic				
Fully operational	1.0000E+0	1.0000E+0	1.0000E+0	1.0000E+0
Failed safe	7.83E-9	7.83E-9	4.90E-8	4.90E-8
Failed uncovered	9.60E-7	9.60E-7	2.40E-6	2.40E-6
Guidance and control				
Fully operational	9.9991E-1	9.9991E-1	9.9977E-1	9.9978E-1
Failed safe	7.99E-5	8.00E-5	2.00E-4	2.00E-4
Failed uncovered	1.03E-5	1.03E-5	2.60E-5	2.61E-5
Pilot				
Fully operational	1.0000E+0	1.0000E+0	9.9999E-1	9.9999E-1
Recoverable failure	2.78E-7	3.59E-7	2.78E-7	7.83E-7
Nonrecoverable failure	4.00E-6	4.00E-6	1.00E-5	1.00E-5

Table 3-9. Probabilities of Operational States

Metric	Probability	
	Upper bound at 4 hours	Upper bound at 10 hours
Insufficient capability independent approach	2.82E-4	7.06E-4
Loss of aircraft before approach lineup	1.03E-5	2.61E-5

IMPACT MODEL

From the description of the system Reliability Model given in the previous section, it is useful to think of aircraft and pilot as an integration of five functions; IAPR RNP navigation, ADS-B/surveillance data link, collision-alerting logic, guidance and control, and pilot. Each function is further characterized by its states of health or degradation, namely, fully operational, degraded, failed safe, or failed uncovered. Each possible system state is associated with an *impact* that represents a potential reduction in system capabilities. The critical question is addressed next.

How System States Impacts Manifest Themselves During the Runway Approach

The correct answer to this question is complex and requires careful study, data analysis, and compilation of information from many expert sources. We have not undertaken such an investigation within the scope of this initial task. However, to illustrate the safety methodology, we assigned different flight tracks for runway approaches as the impact of system functional states. In doing so, we can achieve an association between the system functional state probabilities of the Markov model and the operational safety metrics generated from the Interaction-Response Model. The specific details of the Impact Model presented in this illustration should not be taken as confirmed, validated facts; they are not! However, the objective of the Impact Model, which is to determine and choose a flight track for runway approach that reflects a combined operational capability of the aircraft and pilot that is consistent with a given system functional state, remains valid and important to the realistic evaluation of system safety.

Flight Tracks for Runway Approaches

The flight tracks used in our Impact Model come from a set of eight piloted flight track templates developed by Rockwell-Collins using a Fokker 70 flight simulator [6]. These tracks have been widely used as the set of *intruder trajectories* for testing alerting systems [4,5,6,7,8]. A brief description of each is given in Table 3-10.

Each track is recorded for three different speeds, 130, 145, 160 knots, and under both low- and high-turbulence conditions [6,7,8].

Table 3-10. Flight Tracks for Runway Approaches

Normal approach/landing	Aircraft heading is aligned to runway heading
Blunder of 30°	Aircraft begins runway approach with 30° heading turned away from own runway and toward other runway
Blunder of 15°	Aircraft begins runway approach with 15° heading turned away from own runway and toward other runway
Slow heading change blunder of 10°	Aircraft begins runway approach and slowly deviates from own runway toward other runway by 10° heading change
Slow heading change blunder of 5°	Aircraft begins runway approach and slowly deviates from own runway toward other runway by 5° heading change
Constant bank angle blunder of 5°	Aircraft begins runway approach with 5° bank angle deviation
Fake blunder	Aircraft turns toward other ship's runway followed by return to desired approach path with less than 1,000 feet of lateral deviation
Overadjust blunder	Aircraft drifts off course away from own and other's runway, recognizes error, makes an adjustment to return to own flight path, and overshoots toward other ship's runway with less than 1,000 feet of lateral deviation

For the Interaction-Response Model used in this study, these flight tracks are stored as data files in which a stream of data parametersóposition, heading, bank angle, and speedóis read every 0.4 seconds. Enhancements to the Interaction-Response Model are being made to enable users to adaptively change the flight track in response to system functional states or other "real-time" situations. These enhancements are discussed in Appendix B.

Impact Model

The objective of the Impact Model is to choose a flight track that reflects a combined operational capability of the aircraft and the pilot that is consistent with a given system functional state. For example,

- a *fully operationa*l aircraft can execute a *normal* approach;
- undetected or transient failures could result in unintentional drifting of the aircraft from a normal approach, such as the *fake* or *overadjust* tracks;

- degraded navigational capability could result in low-level or slow blundering such as 5 or 10 degree changes; or
- significant failure of guidance or control capability or significant pilot error may result in pronounced blunder behavior of 15 or 30 degree changes.

The Impact Model mapping used in this application is given in Figure 3-5.

Figure 3-5. Impact Model

Flight track	Markov model subvectors	Probability at t = 4 hours	Probability at t = 10 hours
norm Normal approach/ landing	[N1,~S3,A1,G1,P1]	9.9918e-1	9.9796e-1
Fake: Aircraft fakes blunder toward other ships runway **Oadj:** Aircraft drifts away from own and other's runway, then overadjusts	[N4,~S3,A1,G1,P1]; . [N1,~S3,A3,G1,P1]; . [N1,~S3,A1,G1,P2]	3.65e-6	9.1e-6
sb5: Constant 5° bank angle blunder **sh5:** Slow 5° heading change blunder **Slo:** Slow 10° heading change blunder	[N2,~S3,A1,G1,P1]; . [N1,~S3,A1,G1,P2]	1.72e-4	4.3e-4

Flight track	Markov model subvectors	Probability at t = 4 hours	Probability at t = 10 hours
bl15: 15° heading blunder	[N1,~S3,A1,G3,P1]; [N1,~S3,A1,G1,P3]	7.15e-6	1.80e-5
bl30: 30° heading blunder	[N1,~S3,A1,G3,P1]; [N1,~S3,A1,G1,P3];	7.15e-6	1.80e-5

The notation N1, A1, G1, and P1 refer to the fully operational state of the navigation, alerting, guidance and control, and pilot functions, respectively. The notation ~S3 means any surveillance state except S3. Likewise, N4 is the failed-uncovered navigational state while A3 is the failed-uncovered state for the alerting avionics function. State N2 is the degraded navigational state while P2 corresponds to "recoverable" pilot error. States G3 and P3 are significant error states in the guidance and control and pilot submodels, respectively.

Notice that the "aircraft" is being modeled as a vector of the five functional components. Once this association is defined, the Markov model supplies the probabilities of the vector components. In this illustration, the resulting probability is the product of the component probabilities. However, Markov analysis and modeling is not constrained to "independent" decomposition. Under conditions where

it would be important to model and evaluate functional dependencies, the analysis method can accommodate that type of complexity.

We have evaluated the model for two time periods, 4 hours into flight and 10 hours into flight. These time periods were chosen solely for illustrative purposes. In fact, any time period may be evaluated using the Markov analysis as well as the two aircraft being evaluated at different time periods to simulate an independent but simultaneous approach of two aircraft having been in flight for different time periods.

The fact that Markov analysis can provide time-tagged probabilities of the aircraft system state makes it a superior choice for use in system safety analysis.

INTERACTION-RESPONSE MODEL

Background

The Interaction-Response Model used in this study was developed at Massachusetts Institute of Technology (MIT) under the direction of Professor James Kuchar, Department of Aeronautics and Astronautics during 1995–1996 [5,8]. Draper Laboratory, Inc. obtained this model in January 1997 to expand its capabilities for both the IAPR safety analysis as well as other interesting considerations. Further details of these enhancements can be found in Appendix B.

The original objectives of MITs project were to develop a model of parallel approach scenarios incorporating parameters such as runway configuration, blunder characteristics, human response delays, and type and accuracy of information available to the alerting system; to develop and evaluate a basis for alerting logic (i.e., time to impact or range); and to evaluate alerting thresholds based on a tolerable rate of false alarms.

The performance of the prototype alerting system is evaluated using different approach trajectories developed from piloted flight simulation tests at Rockwell-Collins [6]. These flight tracks were described above. They include normal approaches and 6 categories of blunder trajectories: a slow constant-rate turn at a 5º bank angle; heading changes of 5º, 10º, 15º, 30º; and two cases in which the intruder began a blunder but returned to its approach path before crossing the threatened aircraft's approach path. Separate trajectory data were available for calm and turbulent conditions and at airspeeds of 130, 145, and 160 knots. The same trajectories are used at three runways spacings (1,700, 2,500, and 3,400 feet) and over a series of initial longitudinal spacings (within ±1.5 nautical miles of the threatened aircraft) to cover a range of possible encounter situations. A total of 42,822 simulations using 39 different types of trajectories can be performed for the evaluations.

In the MIT evaluations, the threatened aircraft, the evader, always follows a normal approach path while the intruder follows one of the blunder or normal approach paths from the simulation tests. The alerting logic is implemented only on the evader. If an alert is issued, the evader performs the specified climbing-turn avoidance maneuver. The outcome of each approach is recorded, including (1) whether an alert is generated, (2) whether a collision occurs, and (3) whether an alert is deemed necessary. Six mutually exclusive categories listed in Table 3-11 are used to define the possible outcomes. A collision is defined to occur if separation at any point in the approach was less than 500 feet. An alert is considered to be necessary if a collision would have occurred without an alert. Thus, for example, an alert in a situation in which separation would have been 501 feet without the alert is categorized as unnecessary. Such a definition of unnecessary alert, though strict, is required as a specific performance metric. A pilot's or controller's impression of "unnecessary" is important, but it is more subjective and difficult to use analytically.

Table 3-11. Outcome Categories

Outcome category	Alert issued?	Collision occurred?	Alert necessary?
Correct rejection	No	No	No
Missed detection	No	Yes	Yes
Unnecessary alert	Yes	No	No
Induced collision	Yes	Yes	No
Correct detection	Yes	No	Yes
Late alert	Yes	Yes	Yes

From Table 3-11, one can see that if an alert is not issued at any time during a run, it is classified as either a "correct rejection" (if a collision did not occur) or as a "missed detection" (if a collision did occur). If an alert is issued, the outcome is placed in one of four categories. An "unnecessary alert" is a case where the intruder is not on a collision course; an alert is issued anyway, and a collision is still avoided. If a collision occurs because of the alert, it is classified as an "induced collision." A "correct detection" occurs when a collision is averted because of an alert. Finally, a "late alert" is a case in which an alert is issued, but it is too late to prevent a collision.

In summary, the Interaction-Response Model is a simulation tool providing significant flexibility and timeliness in evaluating very difficult aircraft dynamic behavior and alerting response in encounter situations. It is not meant to replace human in the loop (HITL) evaluations. Indeed, elements of the pilot model including response times and the nature and probability of pilot errors and blunders are all best developed from data extracted from HITL evaluations. Thus, the simulation approach described here goes hand-in-hand with HITL evaluations.

Interaction-Response Model Conditional Safety Statistics

The outcome categories of Table 3-11 can be combined to yield three safety statistics defined as follows:

$$\textit{Probability of reliable operation} = \frac{\textit{\# Correct rej. + \# Correct det.}}{\textit{Total \# of runs}} \quad \text{[Eq. 3-1]}$$

$$\textit{Probability of collision} = \frac{\textit{\# Mis. det. + \# Ind. col. + \# Late alerts}}{\textit{Total \# of runs}} \quad \text{[Eq. 3-2]}$$

$$\textit{Probability of false alarm} = \frac{\textit{\# Unnecessary alerts}}{\textit{Total \# of runs}} \quad \text{[Eq. 3-3]}$$

These three statistics are generated from the Interaction Response model for each pair of flight tracks, and they are *conditional* safety statistics given the flight track simulated. To remove this conditioning, we multiply by the probability of flying the approach with this flight track, namely, the Markov probability of the flight track acquired from the Impact Model. A numerical example is given in the following baseline performance.

BASELINE PERFORMANCE

Table 3-12 shows the results of evaluating the three safety probabilities from the simulation outcome categories.

Table 3-12. Conditional Safety Statistics

Flight tracks [own ship, other ship]	Probability of reliable operation	Probability of collision	Probability of false alarm
[norm_145, norm_154]	1.0000	0.0000	0.0000
[norm_145, fake_145]	0.9544	0.0000	0.0456
[norm_145, oadj_145]	0.9125	0.0000	0.0875
[norm_145, sb5_145]	0.9960	0.0000	0.0040
[norm_145, sh5_145]	0.9854	0.0092	0.0054
[norm_145, slo_145]	0.9872	0.0091	0.0037
[norm_145, bl15_145]	0.9960	0.0018	0.0022
[norm_145, bl30_145]	0.9872	0.0037	0.0091

In this evaluation, eight pairs of flight tracks were evaluated by both the MIT and Draper Interaction-Response Models at the 1,700-foot runway spacing. A total of 183 runs were made for each pair of tracks, and the simulation outcomes were nearly identical for both models.

In each case, the ownship was flying the normal approach at 145 knots. The alerting logic used in this baseline evaluation was supplied by NASAs Langely Research Center. It is a time-/range-based threshold logic. The criterion that invokes an evasive maneuver on the part of ownship is that the othership be predicted to come within 500 feet of ownship within 11 seconds. The pilot response time was set at 2 seconds; the evasive maneuver was a 25 g pull-up to 2,000 feet per minute (fpm) climb, with a 5 degree roll rate to a 30 degree bank angle, and a final heading of 45 degrees. The longitudinal initial condition spacing was incremented at 100-foot intervals thereby producing the 183 runs for each pair of flight tracks.

COMBINING MODEL OUTPUTS: SYSTEM-LEVEL STATISTICS

Combined Results

We now complete the baseline performance example by multiplying the conditional safety statistics by the probability of flying the approach with a given flight track. This probability is obtained from the Markov model. We have evaluated the Markov model at both 4 and 10 hours of flight time prior to beginning the runway approach. This information is shown in Table 3-13.

Table 3-13. Combined Results at 1,700-Foot Runway Spacing

$$\textbf{System safety statistic(t)} = \sum_{\text{Flight tracks}} \textbf{Pr}(\text{Simulation safety stat.} \mid \text{flight track}) \times \textbf{Pr}(\text{flight track})(t)$$

Flight tracks	Conditional simulation safety statistics			Probability flight trk	
	Rel. op.	Collisions	False alarms	T = 4hrs.	t = 10hrs
[norm_145, norm_145]	1	0	0	9.99E-1	9.98E-1
[norm_145, fake_145]	.9544	0	.0456	3.65E-6	9.1E-6
[norm_145, oadj_145]	.9125	0	.0875	3.65E-6	9.1E-6
[norm_145, sb5_145]	.996	0	.0040	1.72E-4	4.3E-4
[norm_145, sh5_145]	.9854	.0092	.0054	1.72E-4	4.3E-4
[norm_145, slo_145]	.9872	.0091	.0037	1.72E-4	4.3E-4
[norm_145, bl15_145]	.996	.0018	.0022	7.15E-6	1.8E-5
[norm_145, bl30_145]	.9872	.0037	.0091	7.15E-6	1.80E-5

System safety statistics		
Rel. op. (4)	=	0.9995
Collisions (4)	=	3.19E-6
False alarms (4)	=	2.82E-6
Rel. op. (10)	=	0.9993
Collisions (10)	=	7.97E-6
False alarms (10)	=	7.05E-6

In addition to the 1,700-foot spacing, we completed a baseline evaluation at both 2,500-foot and 3,400-foot runway spacing. The three sets of safety statistics are given in Table 3-14.

Table 3-14. Safety Statistics at 1,700-Foot, 2,500-Foot, and 3,400-Foot Runway Spacings

1,700-foot spacing			2,500-foot spacing			3,400-foot spacing		
System safety statistics			***System safety statistics***			***System safety statistics***		
Rel. op. (4)	=	0.999531	Rel. op. (4)	=	0.999524	Rel. op. (4)	=	0.999535
Collisions (4)	=	3.187E-6	Collisions (4)	=	3.160E-6	Collisions (4)	=	7.179E-7
False alarms (4)	=	2.819E-6	False alarms (4)	=	1.017E-6	False alarms (4)	=	1.013E-6
Rel. op. (10)	=	0.999329	Rel. op. (10)	=	0.999310	Rel. op. (10)	=	0.999339
Collisions (10)	=	7.968E-6	Collisions (10)	=	7.901E-6	Collisions (10)	=	1.796E-6
False alarms (10)	=	7.047E-6	False alarms (10)	=	2.544E-6	False alarms (10)	=	2.533E-6

As runway spacing changes, only the conditional safety statistics change in response; the scaling probabilities from the Markov model remain the same. Although the actual numerical values should be considered “artificial” and devised for the purposes of this example, the trend of the data is reasonable and what one would expect. As the time in flight increases prior to runway approach, the overall hazard increases and reliable operation decreases. As the runway spacing between aircraft increases, the probabilities of collision and false alarm decrease while reliable operation increases.

In order to demonstrate the approach, we have employed simple models. However, the approach is one wherein models can be appropriately tailored for the level of detail available or desired.

We conclude this chapter with an example of sensitivity analysis to show how this safety methodology can be used to suggest and evaluate design changes leading to improved system performance.

Sensitivity Analysis: An Example

The results of the integrated safety analysis can be used to determine how sensitive the safety statistics are to features of the system architecture, rule and operating procedures, or operational scenarios and environment. By understanding these sensitivities, design improvements can be proposed and evaluated with a cost/benefit tradeoff analysis. But the first step is to isolate the sensitivity.

Referring back to Table 3-13, observe that the slow heading change blunders of 5 and 10 degrees have the highest collision probabilities, 0.0092 and 0.0091, respectively. In addition, these tracks have the largest probabilities of occurrence with a value of 1.72E-04 at 4 hours and 4.3E-04 at 10 hours. Tracing back to the Impact Model and the Reliability Model, we find that the degraded navigation state, N2, is the major contributor to these probabilities of occurrence.

Suppose it were possible to acquire a new, upgraded INS component with a reduced failure rate from 1E-04 down to 1E-05. Replacing the "old" INS component with the new improved element would result in reduced probabilities of occurrence for the slow 5 and 10 degree heading blunders, namely, 5.3E-05 at 4 hours and 1.32E-04 at 10 hours.

Reevaluating the system statistics now yields the following improvements in collision and false alarm probabilities shown in Table 3-15.

Table 3-15. Comparison of Results for Improved INS

Original INS	Improved INS
Collisions (4) = 3.19E-06	Collisions (4) = 1.01E-06
False alarms (4) = 2.82E-06	False alarms (4) = 1.02E-06
Collisions (10) = 7.97E-06	Collisions (10) = 2.515E-06
False alarms (10) = 7.05E-06	False alarms (10) = 2.54E-06

Alternatively, a rules and procedures change could be made whereby independent parallel landings would be precluded when the aircraft is in the degraded navigation state, N2. Costs and benefits would have to be evaluated for both the architecture option and rules/procedures option to arrive at the best course of action to take to improve the overall system performance and reduce the liability of accident and false alarm. In either case, the integrated safety analysis can be exercised interactively and iteratively in order to arrive at the best solution.

Chapter 4
Conclusions

SUMMARY OF SIGNIFICANT RESULTS

We have demonstrated an approach to integrating reliability, performance, and operational procedures modeling into a system safety analysis. Our methodology is distinguished by its ability to merge system design/functionality information with the dynamic parameterization of a system's situation in order to measure accident statistics and reliable system operation. In addition, it can perform sensitivity analyses to identify weak points in the system's operation and design.

Our approach to system safety analysis results from the *integration* of the Reliability Model and the Interaction-Response Model. The Interaction-Response Model provides information regarding the frequency of encounters and the predicted outcome of those encounters as a function of the system's alerting system and ability to resolve encounters. The Reliability Model provides, as a function of time, probabilities associated with the critical systems' availability and failure states. Scaling the operations safety metrics from the Interaction-Response Model by the system-state probabilities from the Reliability Model creates system-level safety statistics.

Products of this analysis include (1) predicted incident (encounter) statistics; (2) predicted accident statistics; and (3) predicted false alarm statistics, as well as system availability and reliability.

As an application of this methodology, we have considered the problem of simultaneous, but independent approaches of two aircraft on parallel runways (independent approaches on parallel runways, or IAPR).

A variety of projects have been undertaken within the past several years to explore alerting systems and cockpit displays for the parallel approach situation. Aircraft are more closely spaced during parallel approach than during any other phase of flight. The potential exists for an aircraft on either runway to deviate off course toward another aircraft on the parallel runway. To increase safety, an alerting system is used to warn flight crews of these blundering aircraft. The goal of the alerting system is to ensure adequate separation between aircraft while allowing parallel approaches to be carried out. With reference to our integrated safety model, these studies represent interaction-response models.

The major limitation of statistical information generated exclusively from an Interaction Response model is that it represents *conditional* safety statistics given

the flight track simulated. To remove this conditioning, we have shown how to apply the probability of flying the approach with this flight track using Markov analysis to compute this probability. The results give system-level safety statistics that can be used to answer important questions such as the variation of reliable operation, accidents, and false alarms as a function of different runway spacings.

The results of the integrated safety analysis can be used to determine how the safety statistics are sensitive to features of the system architecture, rule and operating procedures, or operational scenarios and environment. By understanding these sensitivities, design improvements can be proposed and evaluated with a cost/benefit tradeoff analysis.

AREAS FOR FUTURE WORK

In order to demonstrate the integrated safety analysis methodology, we have employed simple models. We believe the approach is one wherein models can be appropriately tailored for the level of detail either available or desired. Here are several areas of future work in which greater model resolution is desired to more accurately predict the safety of the air transport concept.

Pilot Behavior

The issue of how often a pilot *chooses to ignore or override* alerting system warnings or ground control instructions is certainly important to the safety assessment of any air transport concept. These elements of the pilot model as well as other information relating to response times and the nature and probability of pilot errors and blunders are all best developed from data extracted from HITL evaluations and must continue to be incorporated in the simulation model.

Ground Controller Behavior and Interaction

Realistically speaking, there is no emerging air transport concept that will be fully implemented without progressing through scheduled participation with current day ground control. Certainly, future work must include models for ground control interaction with aircraft.

Environmental Phenomena

The two-aircraft assumption in our model is certainly a simplification that must be removed. Other aircraft in the near vicinity of two aircraft on parallel runways will make the issue of evasive maneuvers and resulting “go-arounds” a major consideration for overall safety. In addition, the forces of wake vortex and environmental and structural obstacles must be included to account for safe approaches as well as safe evasive maneuvers.

Improved Modeling of the Impact of System Failures and/or Pilot Errors on Flight Trajectory

This issue will require careful study, data analysis, and compilation of information from many expert sources. We did not undertake such an investigation within the scope of this initial task. To illustrate the safety methodology, we assigned different flight tracks for runway approaches as the impact of system functional states. In doing so, we achieved an association between the system functional state probabilities of the Markov model and the operational safety metrics generated from the interaction-response model. The specific details of the Impact Model presented in this illustration should not be taken as confirmed, validated facts; they are not! However, the objective of the Impact Model, which is to determine and choose a flight track for runway approach that reflects a combined operational capability of the aircraft and pilot that is consistent with a given system functional state, remains valid and important to the realistic evaluation of system safety.

Desired Capabilities for the Interaction-Response Model

Draper has continued to enhance the capabilities of the MIT Interaction-Response Model. Our current model is completely symmetrized with respect to the capability of ownship and othership. Either aircraft can be assigned any flight track, and each aircraft has an alerting system and is capable of evasive maneuver. These features are clearly desirable in order to realistically simulate the behavior of two aircraft performing independent, parallel approaches. We have discovered some interesting consequences of full-dual capability; these are described in Appendix B and warrant future investigation.

References

[1] Federal Aviation Administration, *Airman's Information Manual-Official Guide to Basic Information and Procedures*, U.S. Department of Transportation, 4 April 1991.

[2] FAA Precision Runway Monitor Program Office, *Precision Runway Monitor Demonstration Report*, Report Number DOT/FAA/RD-91/5, February 1991.

[3] Boeing Commercial Airplane Group, *Parallel Runway Requirement Analysis Study*, NASA Contractor Report 191549, Volume 1, NASA Langley Research Center, Hampton, Virginia, December 1993.

[4] Shank and K. Hollister, "A Statistical Risk Assessment Model for the Precision Runway Monitor System," *ATCA Conference Proceedings*, 1992.

[5] J. Kuchar, "Methodology for Alerting-System Performance Evaluation," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, pp. 438–444, March/April 1996.

[6] Koczo, *Coordinated Parallel Runway Approaches*, NASA Contractor Report 201611; NASA Langley Research Center, Hampton, Virginia, October 1996.

[7] W. Waller and C. H. Scanlon, eds., *Proceedings of the NASA Workshop on Flight Deck Centered Parallel Runway Approaches in Instrument Meteorological Conditions*, NASA Conference Publication 10191, NASA Langley Research Center, Hampton, Virginia, December 1996.

[8] Carpenter and J. Kuchar, *A Probability-Based Alerting Logic for Aircraft on Parallel Approach*, NASA Contractor Report 201685, NASA Langley Research Center, Hampton, Virginia, April 1997.

[9] *Final Draft (Draft 7) of Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*, RTCA Paper No. 097-96/SC181-060, March 4, 1996.

[10] *Draft 3.1 of Minimum Aviation System Performance Specification (MASPS) for ADS-B*, December 16, 1996.

[11] Babcock, A. Schor, and G. Rosch, *Reliability Modeling Methodology for IAPR Safety Analysis*, CSDL-R-xxxx, The Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts, June 1997.

[12] W. Butler and A. L. White, *Sure Reliability Analysis, Program, and Mathematics*, NASA Technical Paper 2764, NASA Langley Research Center, Hampton, Virginia, March 1988.

Appendix A
Reliability Model and Markov Analysis Information

This appendix lists the input files specifying the Markov Reliability Models to the Semi-Markov Unreliability Range Evaluator (SURE) Reliability Analysis program. Table A-1 provides the mapping from the numerical states from each model to the operational states for each function defined in Table A-1.

Table A-1. Reliability Model to Function State Mapping

Operational state of function	Reliability model states
IAPR RNP navigation	
Fully operational	1, 5, 6, 12
Degraded	2, 4, 8, 9, 10, 11, 13, 14
Failed safe	7
Failed uncovered	3
ADS-B/Surveillance data link	
Fully operational	1, 2, 5, 6, 7, 9
Degraded	8, 10
Failed safe	4
Failed uncovered	3
Unknown (aggregate trapping state)	11
Collision alerting avionics	
Fully operational	1, 2, 4, 6
Failed safe	5
Failed uncovered	3
Guidance and control	
Fully operational	1, 2, 4, 6, 7, 8, 9, 10, 11
Failed safe	5
Failed uncovered	3
Unknown (aggregate trapping state)	12
Human factors	
Fully operational	1
Recoverable fault	2
Non-recoverable fault	3

APR RNP NAVIGATION

```
(* IAPR RNP Navigation Reliability Model *)


(* Failure Rates (failures/hour) *)

l_g = 3.0e-5;(* GPS *)
l_i = 1.0e-4;(* INS *)
l_nd = 2.0e-5;   (* Navigation Displays *)
l_np = 1.0e-5;   (* Navigation Processor *)

(* Coverage Probabilities *)

c_g = 0.99;      (* GPS *)
c_i = 0.99;      (* INS *)
c_nd2 = 0.999;   (* Navigation Displays, two on-line *)
c_nd = 0.99;     (* Navigation Displays, one on-line *)
c_np2 = 0.99;    (* Navigation Processor, two on-line *)
c_np = 0.95; (* Navigation Processor, one on-line *)

(* Transition Rates *)

1,2 = l_g*c_g;
1,3 = l_g*(1-c_g) + l_i*(1-c_i) + 2*l_nd*(1-c_nd2) + 2*l_np*(1-c_np2);
1,4 = l_i*c_i;
1,5 = 2*l_nd*c_nd2;
1,6 = 2*l_np*c_np2;

2,3 = l_i*(1-c_i) + 2*l_nd*(1-c_nd2) + 2*l_np*(1-c_np2);
2,7 = l_i*c_i;
2,8 = 2*l_nd*c_nd2;
2,9 = 2*l_np*c_np2;

4,3 = l_g*(1-c_g) + 2*l_nd*(1-c_nd2) + 2*l_np*(1-c_np2);
4,7 = l_g*c_g;
4,10 = 2*l_nd*c_nd2;
4,11 = 2*l_np*c_np2;

5,3 = l_g*(1-c_g) + l_i*(1-c_i) + l_nd*(1-c_nd) + 2*l_np*(1-c_np2);
5,7 = l_nd*c_nd;
5,8 = l_g*c_g;
5,10 = l_i*c_i;
5,12 = 2*l_np*c_np2;

6,3 = l_g*(1-c_g) + l_i*(1-c_i) + 2*l_nd*(1-c_nd2) + l_np*(1-c_np);
6,7 = l_np*c_np;
6,9 = l_g*c_g;
6,11 = l_i*c_i;
6,12 = 2*l_nd*c_nd2;

8,3 = l_i*(1-c_i) + l_nd*(1-c_nd) + 2*l_np*(1-c_np2);
8,7 = l_i*c_i + l_nd*c_nd;
8,13 = 2*l_np*c_np2;

9,3 = l_i*(1-c_i) + 2*l_nd*(1-c_nd2) + l_np*(1-c_np);
9,7 = l_i*c_i + l_np*c_np;
9,13 = 2*l_nd*c_nd2;

10,3 = l_g*(1-c_g) + l_nd*(1-c_nd) + 2*l_np*(1-c_np2);
10,7 = l_g*c_g + l_nd*c_nd;
10,14 = 2*l_np*c_np2;

11,3 = l_g*(1-c_g) + 2*l_nd*(1-c_nd2) + l_np*(1-c_np);
11,7 = l_g*c_g + l_np*c_np;
11,14 = 2*l_nd*c_nd2;

12,3 = l_g*(1-c_g) + l_i*(1-c_i) + l_nd*(1-c_nd) + l_np*(1-c_np);
12,7 = l_nd*c_nd + l_np*c_np;
12,13 = l_g*c_g;
```

```
12,14 = l_i*c_i;

13,3 = l_i*(1-c_i) + l_nd*(1-c_nd) + l_np*(1-c_np);
13,7 = l_i*c_i + l_nd*c_nd + l_np*c_np;

14,3 = l_g*(1-c_g) + l_nd*(1-c_nd) + l_np*(1-c_np);
14,7 = l_g*c_g + l_nd*c_nd + l_np*c_np;

POINTS = 11;

start = 1;
time = 10;
list = 3;
prune = 1e-100;

run nav.out;
```

ADS-B/SURVEILLANCE DATA LINK

```
(* ADS-B/Surveillance data Link Reliability Model *)

(* Failure Rates (failures/hour) *)

l_a = 1.0e-5;(* AHRS *)
l_g = 0.0e-6;(* GPS; Equal to zero to maintain independence of models *)
l_i = 0.0e-6;(* INS; Equal to zero to maintain independence of models *)
l_ad = 2.0e-5;   (* ADS-B Displays *)
l_ap = 1.0e-5;   (* ADS-B Processor *)
l_mt = 5.0e-5;   (* Modulator and Transmitter *)
l_rd = 5.0e-5;   (* Receiver and Demodulator *)
l_an = 1.0e-6;   (* Antenna *)

(* Coverage Probabilities *)

c_a = 0.99;      (* AHRS *)
c_g = 1.0;       (* GPS *)
c_i = 1.0;       (* INS *)
c_ad2 = 0.999;   (* ADS-B Displays, two on-line *)
c_ad = 0.99;     (* ADS-B Displays, one on-line *)
c_ap2 = 0.99;    (* ADS-B Processor, two on-line *)
c_ap = 0.95;     (* ADS-B Processor, one on-line *)
c_mt = 0.99;     (* Modulator and Transmitter *)
c_rd = 0.99;     (* Receiver and Demodulator *)
c_an = 1.0;      (* Antenna *)

(* Transition Rates *)

1,2 = l_a*c_a;
1,3 = l_a*(1-c_a) + l_g*(1-c_g) + l_i*(1-c_i) + 2*l_ad*(1-c_ad2) +
l_ap*(1-c_ap2) + l_mt*(1-c_mt) + l_an*(1-c_an);
1,4 = l_g*c_g + l_mt*c_mt + l_an*c_an;
1,5 = l_i*c_i;
1,6 = 2*l_ad*c_ad2;
1,7 = 2*l_ap*c_ap2;
1,8 = l_rd;

2,3 = l_g*(1-c_g) + l_i*(1-c_i) + 2*l_ad*(1-c_ad2) +
l_ap*(1-c_ap2) + l_mt*(1-c_mt) + l_an*(1-c_an);
2,4 = l_g*c_g + l_i*c_i + l_mt*c_mt + l_an*c_an;
2,9 = 2*l_ad*c_ad2 + 2*l_ap*c_ap2;
2,10 = l_rd;

5,3 = l_a*(1-c_a) + l_g*(1-c_g) + 2*l_ad*(1-c_ad2) +
l_ap*(1-c_ap2) + l_mt*(1-c_mt) + l_an*(1-c_an);
5,4 = l_a*c_a + l_g*c_g + l_mt*c_mt + l_an*c_an;
5,9 = 2*l_ad*c_ad2 + 2*l_ap*c_ap2;
5,10 = l_rd;

6,3 = l_a*(1-c_a) + l_g*(1-c_g) + l_i*(1-c_i) + l_ad*(1-c_ad) +
2*l_ap*(1-c_ap2) + l_mt*(1-c_mt) + l_an*(1-c_an);
```

```
6,4 = l_g*c_g + l_ad*c_ad + l_mt*c_mt + l_an*c_an;
6,9 = l_a*c_a + l_i*c_i + 2*l_ap*c_ap2;
6,10 = l_rd;

7,3 = l_a*(1-c_a) + l_g*(1-c_g) + l_i*(1-c_i) + 2*l_ad*(1-c_ad2) +
l_ap*(1-c_ap) + l_mt*(1-c_mt) + l_an*(1-c_an);
7,4 = l_g*c_g + l_ap*c_ap + l_mt*c_mt + l_an*c_an;
7,9 = l_a*c_a + l_i*c_i + 2*l_ad*c_ad2;
7,10 = l_rd;

8,3 = l_a*(1-c_a) + l_g*(1-c_g) + l_i*(1-c_i) + 2*l_ad*(1-c_ad2) +
2*l_ap*(1-c_ap2) + l_mt*(1-c_mt) + l_an*(1-c_an);
8,4 = l_g*c_g + l_mt*c_mt + l_an*c_an;
8,10 = l_a*c_a + l_i*c_i + 2*l_ad*c_ad2 + 2*l_ap*c_ap2;

9,11 = l_a + l_g + l_i + 2*l_ad + 2*l_ap + l_mt + l_rd + l_an;

10,11 = l_a + l_g + l_i + 2*l_ad + 2*l_ap + l_mt + l_rd + l_an;

POINTS = 11;

start = 1;
time = 10;
list = 3;
prune = 1e-100;

run sur.out;
```

COLLISION-ALERTING AVIONICS

```
(* Collision Alerting Avionics Reliability Model *)

(* Failure Rates (failures/hour) *)

l_nd = 2.0e-5;   (* Alerting Displays *)
l_np = 1.0e-5;   (* Alerting Processor *)

(* Coverage Probabilities *)

c_nd2 = 0.999;   (* Alerting Displays, two on-line *)
c_nd = 0.99;     (* Alerting Displays, one on-line *)
c_np2 = 0.99;    (* Alerting Processor, two on-line *)
c_np = 0.95; (* Alerting Processor, one on-line *)

(* Transition Rates *)

1,2 = 2*l_nd*c_nd2;
1,3 = 2*l_nd*(1-c_nd2) + 2*l_np*(1-c_np2);
1,4 = 2*l_np*c_np2;

2,3 = l_nd*(1-c_nd) + 2*l_np*(1-c_np2);
2,5 = l_nd*c_nd;
2,6 = 2*l_np*c_np2;

4,3 = 2*l_nd*(1-c_nd) + l_np*(1-c_np);
4,5 = l_np*c_np;
4,6 = 2*l_nd*c_nd2;

6,3 = l_nd*(1-c_nd) + l_np*(1-c_np);
6,5 = l_nd*c_nd + l_np*c_np;


POINTS = 11;

start = 1;
time = 10;
list = 3;
prune = 1e-100;

run alert.out;
```

GUIDANCE AND CONTROL

```
(* Guidance and Control Reliability Model *)

(* Failure Rates (failures/hour) *)

l_es = 4.0e-5;   (* Engine Sensors *)
l_ep = 1.0e-5;   (* Engine Processor *)
l_e = 1.0e-5;(* Engine *)
l_ap = 2.0e-5;   (* Alternator and PDU *)
l_d = 2.0e-5;(* G & C Displays *)
l_as = 4.0e-5;   (* Aircraft State and Environment Sensors *)
l_cp = 1.0e-5;   (* Control Processor *)
l_cs = 5.0e-6;   (* Control Surfaces *)

(* Coverage Probabilities *)

c_es2 = 0.99;    (* Engine Sensors, two on-line *)
c_ep2 = 0.99;    (* Engine Processor, two on-line *)
c_e = 0.999; (* Engine *)
c_ap = 0.99;     (* Alternator and PDU *)
c_d2 = 0.999;(* G & C Displays, two on-line *)
c_as2 = 0.99;(* Aircraft State and Environment Sensors, two on-line *)
c_cp2 = 0.99;    (* Control Processor, two on-line *)
c_cs2 = 0.99;    (* Control Surfaces, two on-line *)

(* Transition Rates *)

1,2 = 2*l_es*c_es2;
1,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
1,4 = 2*l_ep*c_ep2;
1,5 = 2*l_e*c_e;
1,6 = 2*l_ap*c_ap;
1,7 = 2*l_d*c_d2;
1,8 = 2*l_as*c_as2;
1,9 = 2*l_cp*c_cp2;
1,10 = 2*l_cs*c_cs2;

2,3 = l_es + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
2,5 = 2*l_e*c_e;
2,11 = 2*l_ep*c_ep2 + 2*l_ap*c_ap +
2*l_d*c_d2 + 2*l_as*c_as2 + 2*l_cp*c_cp2 + 2*l_cs*c_cs2;

4,3 = 2*l_es*(1-c_es2) + l_ep + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
4,5 = 2*l_e*c_e;
4,11 = 2*l_es*c_es2 + 2*l_ap*c_ap +
2*l_d*c_d2 + 2*l_as*c_as2 + 2*l_cp*c_cp2 + 2*l_cs*c_cs2;

6,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + l_e*(1-c_e) + l_e + l_ap +
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
6,5 = l_e*c_e;
6,11 = 2*l_es*c_es2 + 2*l_ep*c_ep2 +
2*l_d*c_d2 + 2*l_as*c_as2 + 2*l_cp*c_cp2 + 2*l_cs*c_cs2;

7,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
l_d + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
7,5 = 2*l_e*c_e;
7,11 = 2*l_es*c_es2 + 2*l_ep*c_ep2 + 2*l_ap*c_ap +
2*l_as*c_as2 + 2*l_cp*c_cp2 + 2*l_cs*c_cs2;

8,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
2*l_d*(1-c_d2) + l_as + 2*l_cp*(1-c_cp2) + 2*l_cs*(1-c_cs2);
8,5 = 2*l_e*c_e;
8,11 = 2*l_es*c_es2 + 2*l_ep*c_ep2 + 2*l_ap*c_ap +
2*l_d*c_d2 + 2*l_cp*c_cp2 + 2*l_cs*c_cs2;

9,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
```

```
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + l_cp + 2*l_cs*(1-c_cs2);
9,5 = 2*l_e*c_e;
9,11 = 2*l_es*c_es2 + 2*l_ep*c_ep2 + 2*l_ap*c_ap +
2*l_d*c_d2 + 2*l_as*c_as2 + 2*l_cs*c_cs2;

10,3 = 2*l_es*(1-c_es2) + 2*l_ep*(1-c_ep2) + 2*l_e*(1-c_e) + 2*l_ap*(1-c_ap) +
2*l_d*(1-c_d2) + 2*l_as*(1-c_as2) + 2*l_cp*(1-c_cp2) + l_cs;
10,5 = 2*l_e*c_e;
10,11= 2*l_es*c_es2 + 2*l_ep*c_ep2 + 2*l_ap*c_ap +
2*l_d*c_d2 + 2*l_as*c_as2 + 2*l_cp*c_cp2;

11,12= 2*l_es + 2*l_ep + 2*l_e + 2*l_ap +
2*l_d + 2*l_as + 2*l_cp + 2*l_cs;

POINTS = 11;

start = 1;
time = 10;
list = 3;
prune = 1e-100;

run g_and_c.out;
```

PILOT

```
(* Human Factors Reliability Model *)

(* Failure Rates (failures/hour) *)

l_in = 1.0e-4;  (* Intermittent Human Failure *)
l_p = 1.0e-6;(* Permanent Human Failure *)

(* Recovery Rates (recoveries/hour) *)

r_in = (1./10.)*(3600./1.);   (* Recovery rate from Intermittent Human
                      Failure *)

(* Transition Rates *)

1,2 = l_in;
1,3 = l_p;

2,1 = r_in;

POINTS = 11;

start  = 1;
time   = 10;
list   = 3;
prune  = 1e-100;
trunc  = 100;

run human_2.out;
```

Appendix B
Draper Enhanced and Modified Interaction-Response Model

Draper has continued to enhance the capabilities of the MIT Interaction-Response model. Our current model is completely symmetrized with respect to the capability of ownship and othership. In fact, the “ships” are referred to as “lftship” (left ship) and “rgtship” (right ship) to correspond with left and right parallel runways. Either aircraft can be assigned any flight track, and each aircraft has an alerting system and is capable of evasive maneuver. These features are clearly desirable to realistically simulate the behavior of two aircraft performing independent, parallel approaches.

The original MIT model did not allow any user adjustment to the simulation processing. We have created a user-friendly, front-end menu that offers the user the following options:

- Assign any single flight track to lftship and any single flight track to rgtship for simulation run. The lftship is no longer restricted to “normal” flight track. The code enhancement ensures that if a blunder track is selected for the lftship, the lftship blunders toward the rgtship’s runway. In addition, the capability to select a single flight track for either or both ships allows for much quicker, efficient testing during code development and flight track generation.

- Assign a customized file for flight tracks for either or both ships for the simulation run. The user can create a file with any number of flight tracks to be processed successively by the simulation. The resulting safety data is output to a separate file and may be viewed at any time during the simulation processing.

- Adjust the alerting system’s update frequency. This feature allows the user to either speed up or slow down the rate at which the alerting logic is updated with aircraft positional data. By exercising this option, the user can test for safety sensitivity to the alerting logic update rate. Ideally, the alerting logic should be updated at a rate that reduces false alarms without penalty of increasing the probability of accidents.

- Adjust the trajectory data of the flight track by inputting desired offset values. This feature allows the user to generate a new flight track from one of the original eight Rockwell-Collins tracks.

- Simulate “bogus” information processing by a ship’s alerting logic. For example, the user specifies a flight track for lftship such as “fake_145,” but specifies that “norm_145” be fed to rgtship’s alerting logic thereby simulating the situation that rgtship thinks lftship is on a normal approach. Exercising this feature allows the user to investigate what happens when misinformation is passed, such as could be the case with undetected or transient failures in the system’s navigational or surveillance processing.

Draper is continuing to test its version of the Interaction-Response model for a variety of flight track combinations as well as alerting logics. With respect to at least one alerting system, we have discovered a subset of scenario runs in which missed detections occurred consistently. This subset consists of combinations of “fake” and “oadj” flight tracks at different speeds. These results are preliminary and warrant further investigation.

Appendix C
Selected Bibliography

Adams, M., S. Kolitz, J. Milner, and A.R. Odoni. “Evolutionary Concepts for Air Traffic Flow Management.” Accepted for publication in *ATC Quarterly* (appeared Summer 1997).

Adams, M., S. Kolitz, and A.R. Odoni. *Evolution Toward a Decentralized Air Traffic Flow Management System.* CSDL-R-2767. C.S. Draper Laboratory, Cambridge, Mass., November 1996.

Adams, M., R. Hildebrant, and W. Weinstein. *ARES Traffic Flow Control Control System Architecture Requirements*. C.S. Draper Laboratory, Cambridge, MA, 1988.

Babcock, P.S., G. Rosch, J.J. Zinchuk. “An Automated Environment for Optimizing Fault-Tolerant Systems Designs.” Reliability and Maintainability Symposium. Orlando, Fla., January 1991.

Bertsimas, D. and S. Stock. “Air Traffic Flow Management in the Presence of En Route Capacity Constraints.” Accepted for publication in *Operations Research.*

Brock, L. D., G. Mamon, and A. Schor. *NDAA Data Link Avionics Alternative 1995 Baseline Suites*. CSDL R-2674. April 1995.

Brock. L., *Compliance Assessment and Validation Plan for the C-141B for Reduced Vertical Separation Minimum Operation*, CSDL R-2773, C.S. Draper Laboratory, Cambridge, MA, December 1996.

Burn, M., J. Carey, J. Czech, and E. R. Wingrove. *The Flight Track Noise Impact Model*, NASA CR-201683, April 1997.

Carlson, P., *Allocating Banks of Flights to Arrival Slots in Reduced-Capacity Situations*, CSDL-T-TBD, C.S. Draper Laboratory, Master’s Thesis, MIT, Cambridge, Mass., June 1997.

Clarke, Michael, *Irregular Airline Operations*, Ph.D. dissertation, MIT, Cambridge, Mass., expected December 1997.

Escobar, Marcos, “The $M(t)/E_k(t)/n$ Queue and Its Applications,” Ph.D. dissertation, MIT, Cambridge, Mass., expected June 1998.

Etheridge, M. R., Technical Description: Aircraft/Air Traffic Management Functional Analysis Model, NASA Contract No. NAS2-14361, February 1997 (1997a).

GPS Integration Alternatives Study Final Report, Contract No. N00030-91-G-0110, Product Manager Avionics AFAE-AV-AEC, C.S. Draper Laboratory, Cambridge, Mass.

Hocker, G. and S. Kolitz, "An Air Traffic Control Simulation Testbed for Flow Management Algorithms," *Proceedings of the Summer Computer Simulation Conference*, July 1993.

Jauffred, Francisco, "Stochastic Optimization of Air Traffic Flows Through Column Generation," Ph.D. dissertation, MIT, Cambridge, Mass., August 1997.

Kaplan, B. J., D. A. Lee, N. Retina, and E. R. Wingrove, *The ASAC Flight Segment and Network Cost Model*, NASA Contract No. NAS2-14361, February 1997.

Kuchar, J.K. and R. J. Hansman, "An Exploratory Study of Plan-View Terrain Displays for Air Carrier Operations," *The International Journal of Aviation Psychology*, 3(1), pp. 39–54, 1993 (1993a).

Lee, D. A., P. F. Kostiuk, B. J. Kaplan, M. Escobar, A. Odoni, and B. Malone, Technical and Economic Analysis of Air Transportation Management Issues Related to Free Flight, LMI Report Number NS501T1, February 1997.

Malone, Kerry, "Efficient Approximations for Dynamic Queueing Systems and Networks," Ph.D. dissertation, MIT, Cambridge, Mass., June 1995.

Milner, Joseph, "An Approach for Dynamic, Real-Time Landing Slot Allocation with Airline Participation," Ph.D. dissertation, MIT, Cambridge, Mass., June 1995.

Nasser, Thomas, "A Framework to Monitor the Safety Perfomance of Transportation Systems," S.M. thesis, MIT, Cambridge, Mass., January 1995.

Odoni, A. R., "Issues in Air Traffic Flow Management," Chapter in *Advanced Technologies for Air Traffic Flow Management*, H. Winter and H.G. Nusser, editors, Springer-Verlag, Berlin, pp. 43–63, 1994.

Odoni, A.R. and R. de Neufville, "Passenger Terminal Design," *Transportation Research*, 26A, pp. 27–35, 1992.

Odoni, A.R., J. Deyst, E. Feron, R. J. Hansman, K. Khan, J. Kuchar, and R.W. Simpson, *Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts*, MIT International Center for Air Transportation, March 1997.

Odoni, A.R., "Models of Airport Operations," *Proceedings of the Aviation Modeling International Symposium*, Federal Aviation Administration, Washington, D.C., June 1993.

Odoni, A.R., *Transportation Modeling Needs: Airports and Airspace*, U.S. Department of Transportation Report, Volpe National Transportation Systems Center, Cambridge, MA, July 1991.

Peterson, M.D., D.J. Bertsimas, and A.R. Odoni, "Decomposition Algorithms for Analyzing Transient Phenomena in Multiclass Queueing Networks in Air Transportation," *Operations Research, 43*, pp. 995–1011, 1995 (1995a).

Peterson, M.D., D.J. Bertsimas, and A.R. Odoni, "Models and Algorithms for Transient Queuing Congestion at Hub Airports," *Management Science, 41*, 1995 (1995b).

Richetta, O. and A. R. Odoni, "Dynamic Solution to the Ground-Holding Policy Problem in Air Traffic Control," *Transportation Research*, pp. 167–185, 1994.

Rifkin, Ryan, "Managed Arrival Reservoirs for Air Traffic Flow Management," June 1997.

Rimm-Kaufman, Alan, "Risk Analysis for a Very Safe Railroad System," Ph.D. dissertation, MIT, Cambridge, Mass., June 1996.

Roberts, E. R., J. A. Villani, and E. R. Wingrove, *Aviation Systems Analysis Capability Quick Response System Report Server User's Guide*, LMI Report Number NS601RD1, October 1996.

Roberts, E. R., J. A. Villani, *ASAC Executive Assistant Architecture Description*, NASA Contract No. NAS2-14361, January 1997 (1997a).

Roberts, E. R., J. A. Villani, and P. Ritter, *Aviation Systems Analysis Capability Quick Response System Test Report*, NASA Contract No. NAS2-14361, January 1997 (1997b).

Robinson, J. D., *A Simulation Testbed for Flow Management Analysis in Air Traffic Control*, CSDL-T-1148, C.S. Draper Laboratory, Masters Thesis in Operations Research, MIT, Cambridge, Mass., 1992.

Rosch, G., P.S. Babcock, M.A. Hutchins, and F.J. Leong. “The Inclusion of Semi-Markov Reconfiguration Transitions into the Computer-Aided Markov Evaluator (CAME) Program,” 8th *DASC Proceedings*, San Jose, CA, October 1988.

Savari, P., *Flight Schedule Generation Problem*, Technical Report, C.S. Draper Laboratory, Cambridge, MA, 1992.

Schor, A.L. and G. Rosch, “Safety Analysis of the Postive Train Separation System,” CSDL R-2642, The Charles Stark Draper Laboratory, Inc., Cambridge, MA, 1994.

Svrcek, Thomas, “A Macroscopic Decision Support System for the Design of Airport Passenger Terminals,” Ph.D. dissertation, MIT, Cambridge, Mass., June 1995.

Terrab, M. and A. R. Odoni, “Strategic Flow Control on an Air Traffic Network,” *Operations Research*, 41, pp. 138–152, 1993.

Venkatakrishnan, C.S., A.I. Barnett, and A.R. Odoni, “Landing Time Intervals and Aircraft Sequencing in a Major Terminal Area,” *Transportation Science, 27*, pp. 211ñ227, 1993.

Vranas, P., D. Bertsimas, and A. R. Odoni, “Dynamic Ground-Holding Policies for a Network of Airports,” *Transportation Science*, pp. 275–291, 1994 (1994a).

Vranas, P., D. Bertsimas, and A. R. Odoni, “The Multi-Airport Ground-Holding Problem in Air Traffic Control,” *Operations Research, 42*, pp. 249–261, 1994 (1994b).

Weinstein, W.W., P.S. Babcock IV, and H.T.K. Leong, “Safety Analysis of ARES,” CSDL R-2013, C.S. Draper Laboratory, Inc., Cambridge, MA, 1987.

Weinstein, W.W. and A.L. Schor, “Safety Analysis of the ATCS,” CSDL R-2098, C.S. Draper Laboratory, Cambridge, MA, 1988.

Wingrove, E. R., D. A. Lee, P. F. Kostiuk, and R. V. Hemm, Estimating the Effects of the Terminal Area Productivity Program, NASA Contract NAS2-14361, January 1997.

Wingrove, E. R. and J. P. Johnson, The Air Carrier Investment Model (2nd Generation), NASA CR-201683, April 1997.

Ying, Kalvin, "A Model to Estimate the Benefits of Improved Weather Prediction for Air Traffic Flow Management" (co-supervised with A. I. Barnett), Master's Thesis, MIT, Cambridge, Mass., September 1995.

Yu, Jung, *Airport Capacity and Regional Weather Modeling*, CSDL-T-1271, C.S. Draper Laboratory, Master's Thesis in Operations Research, MIT, Cambridge, Mass., 1996.

Appendix D
Abbreviations

ADS-B	=	Automatic Dependent Surveillance-Broadcast
AHRS	=	Attitude Heading Reference System
AILS	=	Airborne Information for Lateral Spacing
ATM	=	Air Traffic Management
CDTI	=	cockpit display of traffic information
DGPS	=	Differential Global Positioning System
FAA	=	Federal Aviation Administration
fmp	=	feet per minute
GPS	=	Global Positioning System
HITL	=	human in the loop
IAPR	=	independent approaches on parallel runways
IMC	=	instrument meteorological conditions
INS	=	Inertial Navigation System
MIT	=	Massachusetts Institute of Technology
PDU	=	power distribution units
PRM	=	Precision Runway Monitor
RNP	=	required navigation performance
TSE	=	total system error
VMC	=	visual meteorological conditions
SURE	=	Semi-Markov Unreliability Range Evaluator

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